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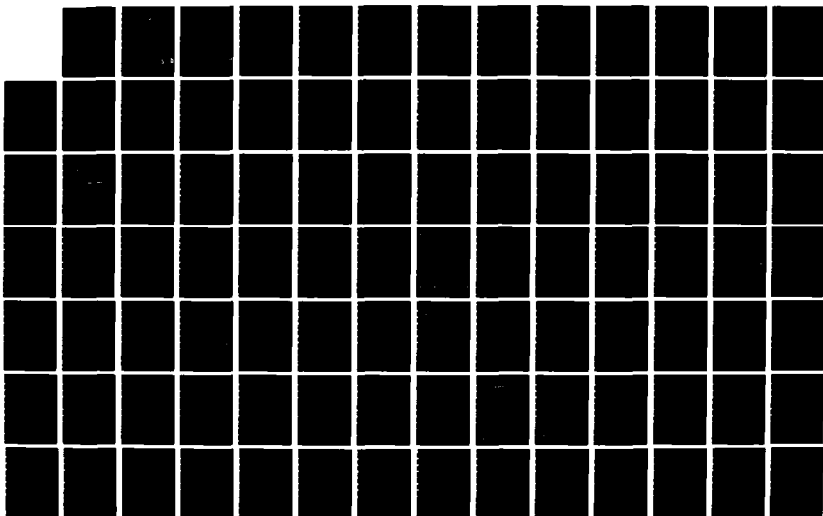
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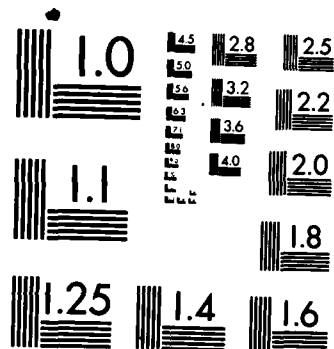
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OF DETERMINING AIRCRAFT
MAINTENANCE INTERVALS

THESIS

David B. O'Hearn
Squadron Leader, RAAF

AFIT/GLM/LSM/85S-59

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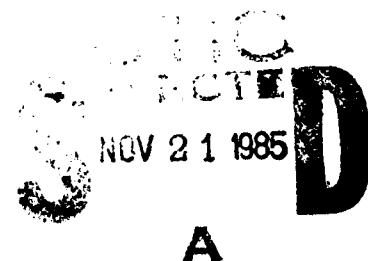
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DEVELOPMENT OF A COMPUTERISED METHOD OF
DETERMINING AIRCRAFT MAINTENANCE INTERVALS

A THESIS

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Logistics Management

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David B. O'Hearn

Table of Contents

	Page
Acknowledgements	iii
List of Figures	vi
List of Tables	vii
Abstract	viii
I. Introduction	1
Background	1
MSG-3	3
General Issues.....	5
Problem Statement.....	6
Research Objective.....	6
Research Question.....	7
Scope and Limitations.....	7
II. Literature Review.....	9
Maintenance Models for Single Components	9
Discrete Time Maintenance Models.....	10
Continuous Maintenance Models.....	10
Age Replacement Models.....	11
Total Time on Test (TTT) Statistic	15
Bergman's Model	17
Application of Bergman's Methodology....	18
Maintenance Models for Multiple Component Complex Systems.....	20
Summary.....	22
III. Determination of Cost Functions For Individual Components	23
Determination of Optimum Age Replacement Intervals.....	23
Determination of the Total Cost Function	24
Validation of the Computer Code.....	25
IV. Development and Analysis of Data.....	26
Data Sources.....	26
Problems with the Failure Data.....	27
Quantity of Failure Data Available.....	29
Deletion of Truncated Records.....	31

	Page
Consideration of Previous Overhauls on Component Lives	31
Cost Data Analysis.....	32
Summary of Assumptions Regarding Data...	36
Total Cost Curves.....	37
V. Development of an Aggregated Total Cost Model	39
Methods for Determining Optimum Servicing Schedules	39
Mathematical Iteration	39
Use of Simulations	40
Use of Heuristics	40
Model Considerations	40
Development of the Heuristic Model	42
Validation of the Model	50
Computer Programme Implementation of the Model	50
Illustration of the Model	51
VI. Conclusions, Implications and Recommendations	55
Meeting the Research Objective	55
Research Questions	56
General	57
Recommendations for Future Research.....	57
Appendix A. Computer Program for TTT Age Replace- ment Computations.....	59
Appendix B. Justification for Deletion of Trun- cated Data.....	64
Appendix C. Comparison of Previous Overhauls on Component Lives.....	66
Appendix D. TTT Curves for Components.....	67
Appendix E. Programme for Determining Servicing Schedules	70
Appendix F. Output from Heuristic Model	77
Bibliography	86
Related Sources.....	89
Vita	90

List of Figures

Figure	Page
1. Illustration of Bergman's Model.....	18
2. Total Cost Curves for Individual Components.	38
3. Illustration of First Approach (Which was Flawed).....	43
4. Illustration of Second Approach (Which was Flawed).....	45
5. Illustration of Heuristic Method.....	48
6. Output From the Heuristic Model.....	52

List of Tables

Table		Page
I.	Number of Complete and Incomplete Data Records for Components Exhibiting More Than One Failure	30
II.	Frequency of Occurrence of Failures...	34
III.	Costs of Failure and Replacement for Components	34
IV.	Output from the Heuristic Model	51

Abstract

Scheduled maintenance is considered one of the largest costs of aircraft ownership. For some components that exhibit an increasing failure rate, this cost can be minimized by changing the components at their optimal age replacement intervals which can be determined using the Total-Time-on-Test statistic. However, the age replacement model treats all components as separate entities and does not recognise economies that can be achieved by changing groups of components at the same time. This study develops a heuristic model for determination of near optimal groupings of components and the replacement intervals for these components. This heuristic model is illustrated using actual field data for a number of components fitted to the C130H aircraft engines operated by the Royal Australian Air Force.

DEVELOPMENT OF A COMPUTERISED METHOD OF DETERMINING AIRCRAFT MAINTENANCE INTERVALS

I. Introduction

Maintenance is a major cost of operating aircraft, both in aircraft downtime and in direct labour and material costs. Recent activities by airlines/aircraft manufacturers and later by the military are designed to reduce these maintenance costs by reviewing the need for various maintenance activities (25:5-6). However, the airlines and the military still use "best guess" and exploratory rather than quantitative decision making techniques to determine intervals for these maintenance activities. If an appropriate operations research technique can be applied to determine optimum aircraft maintenance intervals using past failure data and cost data, large cost savings might be made in scheduled aircraft maintenance.

Background

Historically, aircraft manufacturers have determined maintenance requirements for new aircraft types based on "the common belief that each component" in an airplane "has a unique requirement for scheduled maintenance in order to

protect its inherent level of reliability"(17:9). Then, with experience gained in operation of the new aircraft, additional maintenance requirements have been inserted into the aircraft's maintenance programme so that maintenance has become the predominant cost of aircraft ownership.

In 1968, US airline and aircraft manufacturers realised that something had to be done to rationalize aircraft maintenance. So they developed Handbook MSG-1, "Maintenance Evaluation and Program Development", which contained maintenance procedures for the new Boeing 747 airplane based upon decision-tree logic (17:1). This MSG-1 proved so successful that the airlines and aircraft manufacturers decided to develop a universal procedure applicable to all aircraft types called MSG-2(17). This procedure was then adopted by the United States Air Force (USAF) in 1975 and the Royal Australian Air Force (RAAF) in 1976. The USAF employed aircraft prime contractors to implement the procedure under a programme called Reliability Centered Maintenance (RCM) while the RAAF created two ten-man teams to expand the principles of MSG-2 and apply them to all the RAAF aircraft under the RAAF Analytical Maintenance Programme (RAMP). The MSG-2 procedures were then reviewed and updated in 1980 based upon the experience of the intervening decade and the results were published as MSG-3(18).

MSG-3

The objectives of MSG-3 are:

1. To ensure realisation of inherent levels of safety and reliability of the equipment.
2. To restore safety and reliability to their inherent levels when deterioration occurs.
3. To detect the need for design improvement when inherent reliability is inadequate.
4. To accomplish these goals at minimum cost.

(18:3)

These objectives are achieved by scheduling only that maintenance which is necessary. No additional maintenance tasks which increase maintenance costs are scheduled unless they provide an increase in reliability protection (18:4). To determine if a maintenance task is necessary, a decision-tree logic is used to identify those items whose failure circumstances (i.e., failure mode):

1. could affect safety (on ground or in flight), and/or
2. are undetectable during operations, and/or
3. could have significant operational economic impact, or
4. could have significant non-operational economic impact.

(18:5)

For those items whose failure modes meet this criteria, maintenance tasks are identified and maintenance intervals are determined. The maintenance tasks are readily deduced from engineering data. However, MSG-3 states that "task

intervals/frequency can only be established initially by experienced working group and steering committee personnel using good judgement and operating experience"(18:20). After the initial interval has been established, it is periodically changed from its previous value by some percentage because adequate data is not normally available to support specific interval changes. This process is called "age exploration". To illustrate the "age exploration" process, the guidelines used by the RAAF are:

1. If the component exhibits a high number of unscheduled removals (i.e., more than 50%), the interval for scheduled maintenance should be reduced.
2. If scheduled maintenance detects few faults and there is only a low number of unscheduled arisings, the maintenance interval should be expanded.
3. If the preventive maintenance interval is effective but the condition of the component indicates maintenance is unnecessary (i.e., very little wear on internal parts), the interval should be extended. Conversely, if the component has deteriorated badly, the interval should be reduced.

4. All reductions or expansions of intervals are not to exceed ten percent of the existing intervals unless specific approval is obtained.

The MSG-3 approach to determining maintenance programmes is a dramatic departure from the historical approach of carrying out maintenance on all components regardless of whether the maintenance activity contributes to increased reliability or not. The only area of maintenance programme determination which may be lacking in MSG-3 is a quantitative method for determination of maintenance task intervals.

General Issues

There is a need to develop a quantitative method for determining optimum maintenance intervals for a total system such as an aircraft or an aircraft engine. A preliminary step towards determining the total system maintenance intervals involves determining the optimum maintenance interval for each component independent of the other components in the system. Currently, research on determination of optimum replacement intervals for components has followed two lines of thought. These are:

1. A theoretical failure distribution is estimated for each component based on its failure history. This theoretical distribution is then analysed to determine the optimum replacement interval.

2. Each component follows an unknown empirical failure distribution where a near optimum maintenance interval is deduced from the actual past failure data from the field.

Both of these approaches have limitations which are discussed in Chapter II.

Problem Statement

The RAAF and the USAF need a quantitative, computerised method for determining total system (i.e., aircraft or engine) maintenance intervals. This method should consider the cost functions for each component and aggregate these to determine the suite of servicing schedules which minimizes total cost of maintenance over time. The method must be computerised because the many components contained in a complex system such as an aircraft preclude the use of manual methods.

Research Objective

The objective of this study is to develop a computerised method of determining the optimum maintenance intervals for a complex system such as an aircraft or aircraft engine. To achieve this objective, this thesis is divided into two parts. The first part entails applying actual field data for a complex system to a replacement

model to determine the optimum maintenance intervals at the component level. The cost functions obtained from these replacement models for each component are then combined to form a replacement model for the system. The system model comprises the second part of this research. This model determines the optimal maintenance intervals for the entire system. While analysing the actual field data for each component, a secondary objective is to consider if a component's life is reduced after maintenance compared with its life when new, i.e., does a replacement or repair procedure restore an item to "good-as-new" condition.

Research Question

Can a theoretical computer-based method be developed for optimizing replacement intervals for a complex system with many components?

Provided there is sufficient actual field data, a secondary research question is : How does total component age (as opposed to age since last renewal) affect reliability and so influence the optimum maintenance interval?

Scope and Limitations

The actual field data chosen for this research is that of the C130H aircraft operated by the RAAF. This aircraft is chosen because of the author's detailed knowledge of the aircraft and its components. However, the RAAF only has

twelve C130H aircraft and they have only been in service since July 1978. As a consequence, actual field data is limited. These limitations are discussed in detail in Chapter IV.

II. Literature Review

This chapter reviews the research of a number of statisticians and operations research scientists who are prominent in the fields of maintainability and reliability analysis. The purpose of this review is to ascertain current thought on the development of quantitative methods of determining maintenance intervals for both components and for total systems.

Maintenance Models for Single Components

During the past twenty years extensive research has been done in studying maintenance models of components with stochastic failures in various applications. Barlow and Proschan (3), McCall (20), and Pierskalla and Voelker (26) have surveyed the many models of component reliability reported in the literature and have classified them according to various schemes. In this review, the classification scheme developed by Barlow and Proschan and paralleled by Pierskalla and Voelker is used. This scheme divides the research into two major categories with several subsections in each. The first category is for discrete time maintenance models while the second category deals with continuous time maintenance models.

Discrete Time Maintenance Models

Discrete time maintenance models are where the component is monitored at a discrete point in time and a decision is made to repair, replace and/or restock the item (26:354). Most discrete time maintenance models are based on Markov decision theory with multi-state conditions and involve consideration of the numbers of spare components in inventory (26:355).

Discrete time maintenance models require some information regarding the degree of deterioration at certain points in time. Also, for multi-state discrete time maintenance models, the degree of complexity is beyond the scope of this research. Therefore, consideration of these models is left for future research.

Continuous Time Maintenance Models

Pierskalla and Voelker subdivide the continuous time models into the following categories:

1. The application of control theory to maintenance. This approach is based on maximizing the amount of maintenance activity for a given expenditure at a time t .
2. Age replacement models where an age T is found which provides a unique minimum cost-per-unit time

solution for a component's replacement interval.

3. Shock models where a component is subject to external shocks that occur according to a stochastic process and which affect the failure characteristics of the component.
4. Interactive repair activities where system-wide activities such as opportunistic replacement, cannibalization, multi-stage replacement, and variable repair rate affect the system.

(26:355)

The continuous maintenance model category of interest to this thesis is the age replacement theory because this provides a unique minimum cost-per-unit time solution for each component. Therefore, age replacement models are now reviewed below in more depth.

Age Replacement Models

Age replacement is the policy of replacing functioning components at some age T , called the age replacement interval or at failure whichever event occurs first (1:467). The early models of age replacement, as reported by Barlow and Proschan (3), determine an optimum age replacement policy by minimizing the long run average standardised cost for the component per unit of time. Hence, long run average cost per unit time can be expressed as

$$C(T) = \frac{c + F(T)}{\int_0^T (1 - F(t)) \cdot dt} \quad \text{where } F(T) = \text{failure distribution function}$$

$$c = c_2 / (c_1 - c_2)$$

c_1 = cost of failure

c_2 = cost of replacement

The numerator is the expected standardised cost associated with each replacement and the denominator is the expected time between replacements (8:467).

Several authors including Glasser(13); and Kamins and McCall(15) discuss Barlow and Proschan's age replacement model for specific probability distributions such as the truncated normal, log-normal, gamma, and Weibull distributions. Glasser also presented a number of graphs which provide quick solutions for these models (13:83-91; 15:9-46). Fox considered discounted costs on the age replacement model and derived an integral equation which can be solved to obtain a unique optimal value of T (12:536). Scheaffer suggested that as many components start to wear out their operating costs increase so that increasing cost factors should be included in any component age replacement model. For example, as an auto engine wears, the engine consumes more fuel and oil than when it is new. So, Scheaffer applied both constant (linear) cost factors and exponentially increasing cost factors to the original models developed by Barlow and Proschan (28:139). Taylor then tied

together the consideration of shocks, total cumulative damage to date, and cost parameters in his model of age replacement for exponentially distributed failure probabilities (30:1-2).

Expensive and complicated components are often repaired and not replaced at failure. Barlow and Hunter defined two types of maintenance policy. Type I policy is the simple age replacement policy while Type II policy includes the restoration of a failed component to operation without affecting its failure rate by undertaking a process of minimal repair. This Type II policy assumes all failures before time T are handled by minimal repair (2:90-91). Type II age replacement theory has since been expanded by Tilquin and Cleroux to consider cost adjustments over an infinite time span (31:243). Boland and Proschan have generalised this Type II theory to consider the age T which minimizes either total expected cost of repair and replacement over a fixed time interval or the total expected cost per unit time over an infinite time span (6:1183). Block, Borges and Savits have used this theory to develop "a general model which incorporates minimal repair, planned and unplanned replacements, and costs which depend on time" (5:1). This model considers both infinite and finite time spans when optimizing its long run average costs (5:1).

All of the age replacement models reviewed assume the decision-maker has complete information on:

1. the current state of the system,
2. the probability law governing the systems stochastic behaviour (i.e., its failure distribution is a known theoretical distribution), and
3. the cost implications of replacement at failure (c_1) and of replacement before failure (c_2).
(26:373)

However, for the aircraft components considered in this research, the underlying theoretical failure distributions are unknown. If a theoretical distribution is chosen based on the data, Doumit and Pearce advise that there are three types of uncertainty which create potential for errors. These are:

Type I uncertainty: a sampling error caused by the sample data not being representative of the population;

Type II uncertainty: selection of a theoretical distribution that does not accurately represent the data;

Type III uncertainty: the uncertainty involved in
selecting the "most suitable" distribution.
 (11:3-4)

To avoid Type II and Type III error, a solution technique for an age replacement model which does not rely on a theoretical failure distribution is required. Such a technique involves the Total Time on Test (TTT) Statistic discussed by Barlow and Campo (1) and applied to the age replacement model by Bergman (8).

Total Time on Test (TTT) Statistic

Barlow and Campo describe a method for analyzing data that is called the Total-Time-on-Test Statistic, T_j , where

$$T_i = \sum_{j=1}^i (n - j + 1) (t_{(j)} - t_{(j-1)})$$

here,

$t_{(i)}$ is a value from the ordered set of life observations from the distribution F such that $t_{(1)} < t_{(2)} < \dots < t_{(i)} < \dots < t_{(n)}$. Since $t_{(1)}$ represents the life of the first component that failed, and $t_{(2)}$ the life of the second, etc., then it follows that n components all lived $t_{(1)}$ units of time, $n-1$ components lived $t_{(2)}$ units of time, and only one component lived $t_{(n)}$ units of time. Thus $t_{(i)}$ represents the life of the i th component in the ordered set of n lifetimes, where $t_{(0)}=0$.

T_i is the total time on test statistic and represents the total life generated by the n components in the interval $(t_{(0)}, t_{(i)})$, where a portion of the n components survived throughout the interval and the remainder failed during the interval.

U_i is the scaled total time on test statistic and is equal to the ratio of T_i to T_n . Thus, U_i represents the proportion of the total life generated by the n components during the interval $(t_{(0)}, t_{(i)})$.

(1:452-457)

The TTT Statistic is graphically represented by plotting U_i against i/n . This relates the proportion of total life generated by a component to the cumulative probability that it fails at a given point in time. Barlow and Campo show that an exponential failure distribution (constant failure rate) has a TTT plot that is a 45 degree line from the origin to the point (1,1).

Barlow and Campo advised that the TTT Statistic could accomodate the following types of incomplete data:

1. Grouped data, i.e., data gathered within a specified time interval.

2. Truncated data, i.e. Data gathered from observations that terminated at a fixed time before all items had failed.
3. Censored data, i.e. Data gathered from tests where all testing ceased after the r -th failure.
4. Failure data containing withdrawals i.e. Groups of data with some data values unobserved (unknown).
(1:461-463)

Bergman's Model

Bergman applied Barlow and Campo's TTT statistic to Barlow and Proschan's age replacement model to provide a useful means of estimating optimum age replacement intervals when only observational data are available and the underlying failure distribution is not known with certainty. He found that by drawing a tangent between the TTT curve and the point $(-c, 0)$, (where $c = (c_2) / (c_1 - c_2)$), the index of the failure life that correspond to the tangent point (j_0) could provide an estimate of the optimal age replacement interval as t_{j_0} . Also, if the number of observations is large enough, there is a high probability that the estimated replacement interval is close to the true optimum interval (8:469).

This graphical approach for age replacement by Bergman allows empirical probability distribution functions for

failures of aircraft components to be readily determined from incomplete data as well as from complete data. Thus, there is no need for fitting a theoretical distribution and

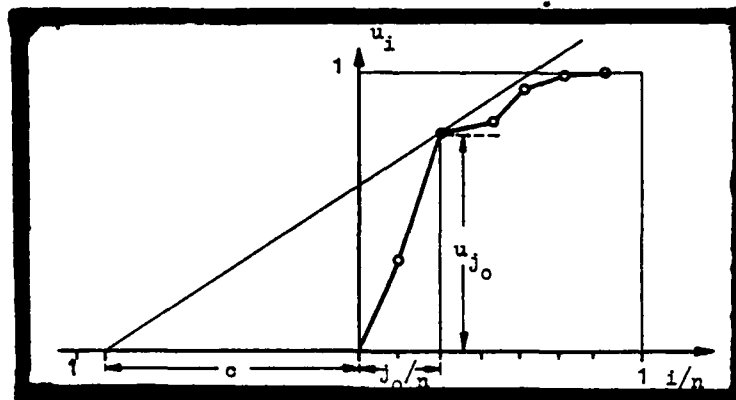


Figure 1. Illustration of Bergman's Model
Source : (8:469)

risking Type II and Type III errors - a problem which would be faced if using other methods for modelling age replacement for aircraft components. Bergman's method provides a simple graphical method which uses observational data to provide a non parametric age replacement policy. It also provides an easy method for carrying out a sensitivity analysis on costs.(8:469)

Application of Bergman's Methodology

Recent applications of Bergman's "age replacement" methodology have been reported by Roclivitch and Beckwith (7), Mariotti (19) and Brill (9). Roclivitch and Beckwith demonstrated Bergman's model by determining the optimum

replacement interval for the KT-73 Inertial Measurement Unit (IMU) installed in the A7-D. They found the IMU exhibited an exponential rate so they concluded the IMUs should not be replaced until failure (7:92-93). Roclivitch and Beckwith also recommended that future research using Bergman's model should consider items that exhibit an increasing failure rate (7:98).

Mariotti used Bergman's methodology on actual field data for Travelling Wave Tube Assemblies from various on-orbit satellite systems to determine if preventive maintenance was a feasible maintenance category for future satellites. He concluded that preventive maintenance was not suitable for current satellite designs because the components exhibited decreasing failure rates (DFR). However, his research did show that Bergman's methodology has great potential for use within the decision logic of Reliability Centered Maintenance for on-condition or hard time maintenance decisions (19:56).

Brill applied Bergman's age replacement technique to determination of optimum replacement intervals for five F100 aircraft engine components. He also carried out a sensitivity analysis on the cost data used in his application of the TTT model, and he found that the TTT model provided direct improvements in reduced maintenance costs (9:115). Brill also concluded:

The procedures for data reduction, constructing TTT plots, and defining standard costs can be easily programmed for computer solution. Mathematical programming methods can possibly be used to optimally aggregate the individual intervals for a set of components. (9:116)

Having reviewed the "age replacement" maintenance model for single components, the current theory for multiple component systems is now reviewed.

Maintenance Models for Multiple Component Complex Systems

Reports of age replacement models for multi-component complex systems have yet to appear in the literature. Generally, researchers tend to treat a complex system as a single entity then use the component maintenance model already discussed to obtain a single optimum age replacement interval for the system.

Those researchers who have considered multi-component models have concentrated their research in two directions:

1. the study of redundant systems where the reliability of the standby system is the subject of the research; or
2. the study of two-component systems.

Numerous papers by such researchers as Jorgensen and Radner (14); Dhillon (10); Nakagawa and Osaki (22),

(23),(24); Mine and Asakura (21); and Liebowitz (16) discuss the determination of availability, reliability, mean times between failures and other aspects of two-element redundant systems. Of the research on two-component series systems, Sethi considered a model where an opportunistic cost exists so that if one unit fails, the total cost of changing both units is discounted. From this situation, he determined an age T , such that if component #2 fails when component #1 has an age $>T$, it is economical to change both components. Sethi concluded that for systems with more than two components, there is no simple method for solving the problem (27:446). Vergin and Scriabin considered dynamic programming for a two-component system. From their research, they concluded that the near-optimal maintenance policies developed from their dynamic programming model could provide substantial savings. However, they also said that computation time limits the direct application of their dynamic programming model to the analysis of only a few components (32:297-304).

Another approach involves the use of simulation models. Smith developed a detailed cost model for the F100 engine on the F-15 aircraft. He then simulated this cost model for a 20 year life cycle based on three different maintenance intervals for different engine components (29:26-28). This approach provided information on which of the three maintenance intervals was most appropriate; however, it might not result in an optimal solution.

Summary

To summarize, the most suitable age replacement policy for individual components is the Bergman method based on the TTT statistic when actual field data is used. Also, no "easy-to-use" procedure has been found for optimizing the maintenance intervals for a complex system which contains many components each with individual optimum age replacement intervals. Therefore, development of a technique for minimizing total costs of maintenance of a complex system containing many components is required.

III. Determination of Cost Functions For Individual Components

This chapter details the methods used to determine the cost functions for each component in a complex system and the optimal age replacement intervals for these individual components which minimizes the respective cost function.

Determination of Optimum Age Replacement Intervals

A description of the model for determination of age replacement intervals is discussed in Chapter II. This model is developed for complete failure data. For incomplete data, Barlow and Campo suggest the following scaled total-time-on-test statistics:

1. Truncated data - if the observations terminate at time L and if $k < n$ failures are observed, then $T(X_i)/T(L)$ is plotted against i/k .
2. Censored Data - if the testing stops at the r -th failure then $T(X_i)/T(X_r)$ is plotted against i/r .
3. Failure Data Containing Withdrawals - if a component i is lost to observation at time x_i and $Z_i < x_i < Z_k$, and where $Z_0 < \dots < Z_i < \dots < Z_k$

are the observed failure times, then $T(Z_i)/T(Z_k)$ is plotted against i/k but the life x_i is included in the computation of the TTT statistic. (1:461-463)

With actual field data used in this research, truncated data and withdrawn observations are experienced. Therefore, Bergman's age replacement model (see Chapter II) was modified to handle these observations. This model was then developed as a Basic computer programme which is contained at Appendix A.

Determination of the Total Cost Function

The cost function $C(t)$ for the age replacement model is defined as:

$$C(t) = c_1.F(t) + c_2.R(t) / \int_0^t R(x).dx$$

where c_1 = cost of failure

$F(t)$ = Probability of failure

c_2 = cost of replacement

$R(t) = 1-F(t)$ = Probability of survival

$$\text{Thus } C(t) = \{c_1.F(t) + c_2 - c_2.F(t)\} / \int_0^t R(x).dx$$

$$\text{Therefore, } C(t)/(c_1-c_2) = \{C + F(t)\} / \int_0^t R(x).dx$$

$$\text{where } C = c_2/(c_1 - c_2)$$

Now, from Bergman's age replacement model, i/n is an estimate of the probability of failure $F(t_i)$, and $T(t_i)/n$ is an estimate of $\int_0^t R(x).dx$. Thus, the cost function can be

estimated as:

$$C(t) = (C + i/n) / \{T(t_i)/n\} * (c_1 - c_2) \quad - \text{Eqn 1}$$

Validation of the Computer Code

The computer programme at Appendix A was extensively tested to confirm there were no syntactical computer code errors. The programme logic was also checked by using hand calculations. External validation of the computer programme and the data was not possible because the quantity of data was so small. This lack of data is further discussed in Chapter IV.

IV. Development and Analysis of Data

This chapter examines the source of the data and the procedures used to collect and analyse this data for use in the TTT cost model described in Chapter III. Also discussed are problems incurred with using actual field data.

Data Sources

The complex system chosen to illustrate this research was the engine fitted to the C130H aircraft. This engine is the Allison T56-A-15 turboprop engine. The reasons why this system was chosen are:

1. the author has a detailed knowledge of the system;
2. the T56-A-15 engine is in service with both the USAF and the RAAF;
3. the RAAF C130H aircraft are all operated in the same role of tactical air transport by the same Squadron from the same location. Hence all components should experience the same operating conditions during their lifetimes.

To obtain the failure data, records of failures and removals for attaining hard time limits (withdrawals) were obtained from RAAF component history logs called MMILOGS. These MMILOGS are held in a computer data base at the operating unit.

Cost data were obtained from RAAF report MAARS 22, which records manhours expended while gaining access to the component, repairing the component, and in the administrative management of the repair process.

Problems with the Failure Data

When the failure data was received from Australia, a number of problems were noted which reduced the quality and quantity of the data. These problems are:

1. The RAAF took delivery of its C130H aircraft in 1978. As the C130H fleet had a high rate of effort in the late 1970's, it was anticipated that most engines would have over 7000 hours operating time. However, the data showed that most of the engines have only reached about 3500 hours of expended life. This is probably due to Government cut-backs in Defence spending during the 1980's.
2. The engine components are more reliable than anticipated. As the C130H engine has been in service with the USAF since the mid-1970's and it

is based on a proven design, many low reliability components have been modified over time to increase their reliability. This low failure rate coupled with the low flying rate means relatively few component failures have been recorded.

3. The RAAF C130H engines are overhauled by a civilian contractor, namely QANTAS, which is Australia's overseas airline. To allow QANTAS to survive during the economic recession of the late 1970's and the price war following de-regulation of US airlines, the Australian Government made a political decision to give QANTAS extra military work. This resulted in a number of C130H engines being overhauled when they had less than 2000 hours of expired life since new. This decision reduced even further the number of engines which had acquired enough operating life to experience component failures.
4. The RAAF introduced a computer-based maintenance management system called CAMM in 1980. A shortage of computer memory has since meant that complete history logs are only kept for selected components which are safety-critical or of interest to unit management. Abbreviated logs (i.e., logs of the last five entries only) are kept for some other

components. However, many components have no history logs recorded.

5. Some components have been repaired instead of overhauled which masks their real life. For example, the Actuator Flap Oil Cooler consists of two sub-assemblies - an Actuator and a DC Motor. Both of these sub-assemblies can be replaced without affecting the records for the higher assembly. Hence, an Actuator Flap Oil Cooler may have had three new DC Motors and two new Actuators but never have experienced an overhaul or a failure according to its component history log.

Quantity of Failure Data Available

Due to the problems just discussed, the quantity of data available was substantially less than anticipated. The MMILOGS received from Australia contained records for 47 engines with each engine containing records for 56 components. This means at least 2668 records (58 x 46) were anticipated. However, after reviewing the data, the number of records obtained were:

No. of components with withdrawn data & no failures	= 18
No. of components with withdrawn data & failures	= 16
Of these, No. of components with >4 failures	= 2
No. of components with >2 failures	= 11
No. of components with only one failure	= 5

The remainder of the components only had truncated life records which reflected the components life when the hardcopy MMILOG report was extracted from the computer.

As the TTT model requires more than one failure data point, only those components with two or more failures are considered in this research. These components and their respective numbers of data records are listed in Table I.

TABLE I

Number of Complete and Incomplete Data Records
For Components Exhibiting More Than One Failure

Component	Failures	No. of Records	
		Withdrawals	Truncations
Act Flap Oil Cooler	4	23	46
Generator AC Engine	2	17	46
Starter Pneumatic	13	9	31
Control Fuel	4	7	46
Valve Temp Datum	3	7	46
Co-ordinator Assy	3	3	47
Switch Speed Sens	3	4	47
Valve Speed Sens	3	5	47
Tank Engine Oil	6	2	47
Cooler Eng Oil	2	4	47
Tx Engine Oil Press	4	-	40

Deletion of Truncated Records

As each record contained truncated data reflecting the life of the component at the date the MMILOG report was produced, it was decided to delete these records to reduce some of the "noise" in the data. To test the effect of this decision, the mean of the truncated lives was computed for each of the components exhibiting more than one failure. A mean of the mean truncated lives was then calculated and compared against the mean of the computed lives using the t test for a 95% confidence interval. This calculation is at Appendix B. It shows there is insufficient evidence to conclude that the two data populations are statistically different.

Consideration of Previous Overhauls on Component Lives

Consideration of previous overhauls on component lives is important to determine if the repair or replacement process restores the component to a "good-as-new" condition. If the component is not restored to a "good-as-new" condition, the maintenance schedule model developed in Chapter V should be modified by changing the cost function to reflect reductions in component lives after overhaul.

Only one component had sufficient failure data to be able to compare its average life during its first life cycle (i.e., since new) to its average life during its second life cycle (i.e., since overhaul). This component was the Actuator Flap Oil Cooler. It had 20 records of failures or

withdrawals in its first life and seven records of failures or withdrawals since its overhaul. None of the components has yet to receive a second overhaul.

To determine if a significant difference existed in the lives before and after overhaul, the means of the lives were compared using the t test as shown in Appendix C. This test shows there is a significant difference between the means. Therefore, a need exists to expand the TTT model to consider the effect of the number of renewal cycles since new on the component's optimal age replacement interval. However, this is outside the scope of this research. In this thesis, it is assumed that all lives for a given component type can be grouped together regardless of the number of renewals, i.e., perfect repair to a "good-as-new" condition is assumed.

As the model developed in Chapter V assumes all of the components are "good-as-new", the consequence of this assumption is that the optimum age replacement intervals for the components are more pessimistic than if only data for new (i.e., not previously overhauled) components was used. This means components are changed at more frequent time intervals than if perfect repair is assumed.

Cost Data Analysis

For this research, all costs are to measured in terms

of manhours. This unit of measurement has been selected because it ignores affects of economic inflation and different prices for spare parts purchased from different sources. The MAARS 22 report lists the manhours expended at operating, intermediate and depot levels for obtaining access to a component, "hands on" repair or overhaul of the component, and administration of the repair process. To determine the replacement cost c_2 of each component, the operating, intermediate and depot level "hands on" costs are averaged for all "non-failed" item records of the component in the report.

Determination of the cost of failure, c_1 , depends on internal damage to the component and the effect of the failure on the rest of the engine. Failure of some components may only result in loss of some mission capability while failures of other components may result in an inflight engine shutdown and abort of the mission or total destruction of the engine. Table II shows the affects of failure of each component.

Costs for internal damage for each component are obtained from the MAARS 22 report. As the cost of reduced mission capability cannot be readily determined, it has been estimated as double the cost of the internal failure. The cost of an engine shutdown and mission abort has been estimated as 200 manhours by personnel at the operating

TABLE II
Frequency of Occurrence of Failures

Component	No Effect On Mission	Reduced Mission Capability	Engine Shutdown & Abort	Possible Engine Destruction
Act Flap Oil Cooler	.405	.595		
Generator AC Eng	.019	.036	.945	
Starter Pneumatic	.242	.606	.152	
Control Fuel	.385	.455	.159	.001
Valve Temp Datum	.611	.389		
Co-ordinator Assy	.057	.231	.692	.020
Switch Speed Sens	.250	.375	.375	
Valve Speed Sens	.565	.435		
Tank Engine Oil	.143	.462	.385	.010
Cooler Eng Oil	.222	.556	.222	
Tx Eng Oil Press	.088	.088	.824	

TABLE III
Costs of Failure and Replacement for Components

Component	^{C₁} Cost of Failure	^{C₂} Cost of Replacement
Act Flap Oil Cooler	25	8
Generator AC Eng	240	40
Starter Pneumatic	245	20
Control Fuel	2080	80
Valve Temp Datum	64	32
Co-ordinator Assy	2025	9
Switch Speed Sens	220	10
Valve Speed Sens	80	40
Tank Engine Oil	2005	1
Cooler Eng Oil	200	1
Tx Engine Oil Press	220	1

unit. The cost of total engine destruction is approximately 2000 manhours based on repairs to C130A and C130E engines which have destructively failed in the past.

From the MAARS 22 report, the frequency of occurrence of each of the failure effects was counted and the probability of occurrence determined (See Table II). Using this frequency and the costs of each affect, a value of c_1 has been determined. This value and that of c_2 are listed in Table III.

Application of the TTT Model

The failure life and cost data was applied to the computer programme (see Appendix A) of the TTT cost curve model described in Chapter III. The resulting TTT curves are shown in Appendix D.

From these TTT curves the following observations are made:

1. the Tank Engine Oil exhibits a decreasing failure rate,
2. the Tx Engine Oil Press exhibits a "U-shaped" hazard function which means it exhibits both infant mortality (DFR) and wearout (IFR), and
3. the remainder of the components exhibit an

increasing failure rate (IFR) which means they have unique optimum age replacement intervals.

The infant mortality for the Tank Engine Oil can be explained by the nature of the component. It is a fabricated aluminium tank with welded seams. Its only failure mode is cracking of the welds causing oil leakage. As it is difficult to determine if a weld is sound, any poor quality welds usually manifest themselves as failures during the first 2000 flying hours. After 2000 flying hours, those tanks that have not leaked can be assumed to have good welds.

The Tx Engine Oil Press is an electrical transducer which detects the engine oil pressure and transmits it to a cockpit gauge. Since it has no mechanical parts subject to wear, it is difficult to explain why it exhibits both infant mortality and wearout. This may be a statistical anomaly due to scant data and that more failure data would reveal an exponential failure pattern.

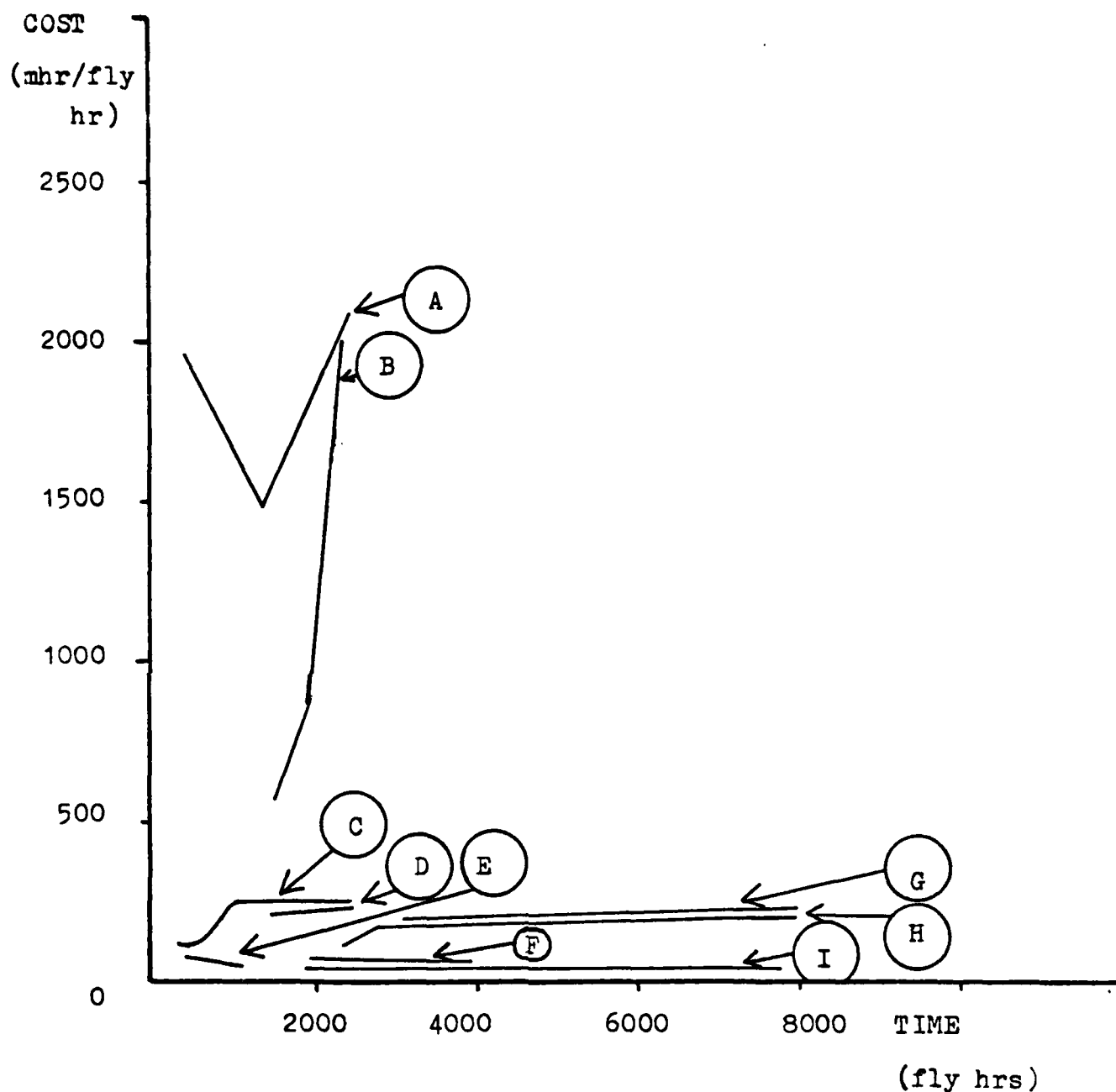
Summary of Assumptions Regarding the Data

For a number of reasons, the actual field data was more difficult to obtain than was expected. This meant a number of assumptions had to be made. These assumptions were:

1. Failure data was only available for eleven components. It was assumed that these eleven components were representative of the total population of components for the C130H engine and that this could be proven when additional failure data becomes available in the future.
2. Deleting truncated life data from the TTT model did not affect the use of the model.
3. The number of previous renewals did not affect the unique age replacement interval for each component. There is some evidence to indicate that this assumption may not be true; however, it was still used for simplicity in illustrating use of the TTT model.
4. As approximations were made in determining cost data for use in the TTT model, the results obtained were considered not to be very sensitive to variations in costs.

Total Cost Curves

The total cost curves for each of the components in Appendix D which exhibit IFR are shown in Figure 2. Chapter V now describes the methodology developed by this research to aggregate these total cost curves.



Key:

A Co-ordinator Assy
 B Control Fuel
 C Starter Pnuematic
 D Cooler Eng Oil
 E Valve Speed Sens

F Valve Temp Datum
 G Generator AC Engine
 H Switch Speed Sens
 I Act Flap Oil Cooler

Figure 2. Total Cost Curves for Individual Components

V. Development of an Aggregated Total Cost Model

In this chapter, a model is developed to aggregate the total cost curves shown in Figure 2. These cost curves were obtained from equation 1 which was developed in Chapter III.

Methods For Determining Optimum Servicing Schedules

For a complex system, there are three possible approaches available for determining the optimum mix of components in each servicing schedule and the interval for each of these schedules. These approaches are:

1. Mathematical iteration;
2. Use of simulations; and
3. Use of heuristics.

Mathematical Iteration

Mathematical iteration involves computing the cost of each possible combination of components. This is done by summing the cost functions for all combinations of maintenance intervals for the n components taken one at a time, two at a time, then three at a time and so on up to all n at a time. The number of maintenance intervals with the lowest value of the total costs obtained from these "iterations" then provides an estimate of the optimum maintenance cost and indicates the combination of

components in each servicing schedule which achieves this minimum cost. This approach involves a great deal of computation so it is considered infeasible for a very complex system.

Use of Simulations

As discussed in Chapter II, simulations are very expensive in terms of time and cost. Also, they do not provide optimal solutions. Instead, simulation models only determine probable outcomes for a set of constraints set up in the model. Hence, simulation models are not considered useful for developing an optimal suite of servicing schedules.

Use of Heuristics

Heuristics are "rules of thumb" used to solve problems. The heuristic approach is useful for solving this problem because it eliminates some of the combinations of components which would clearly not result in the lowest cost suite of servicing schedules. Therefore, this approach is used to develop the aggregated total cost curve and hence an estimate of the optimal combination of components and schedules to achieve minimum cost.

Model Considerations

Before developing the model, some factors which impact development of the model are discussed.

One of the limitations with using empirical distributions based on actual field data is that the empirical distribution for each component is only valid over the range available for actual field data on that component. That is, the empirical distribution for all components may not cover the same domain. This means that the ranges of some of the total cost curves shown in Figure 2 are mutually exclusive and ought not be added together. If the ranges of some of the components were extrapolated to allow all of the components to be added together, unwanted errors could be introduced into the results. Therefore, extrapolation of the ranges is not considered in the heuristic model developed in this Chapter.

In addition to the cost of replacement of each component, the model must also consider such costs as gaining access to the components, administration of the servicing and other overheads. Clearly these costs are less per component if more than one component is changed at any one time (i.e., economies of scale are achieved). The model considers this fact; however, for simplicity, these costs are assumed to be constant for each servicing.

For the C130H engine, the costs detailed below are incurred for each servicing regardless of the number of components changed during the servicing. These costs were obtained from the RAAF maintenance squadron.

Cost of paperwork preparation & administration = 2 mhrs
Cost of setting up workstands, removing cowl,
getting tools, etc. = 4 mhrs
Cost of engine runs for leak checks after
maintenance activity = 5 mhrs
TOTAL ADMINISTRATIVE COST = 11 mhrs

As the administrative cost is assumed to be a constant cost per servicing, the 11 manhours must be divided by the time (in flying hours) at which the servicing occurs to scale the administrative cost in terms of units of flying time so that it can be added to each component's cost function.

In the next Section, a scaled constant administrative cost is used in a heuristic model development designed to consider the different ranges of the component cost curves.

Development of the Heuristic Model

In the development of the heuristic model, a number of approaches were tried. The first approach was to select the component with the steepest slope around its minimum cost point. Then add the component with the next steepest slope to form a schedule of two components with the interval set at the minimum cost point of the curve with the steepest slope. This procedure was then continued for all components for all feasible numbers of schedules. This approach is illustrated in Figure 3. Looking at the magnitude of the gradients (slopes) about the minimum cost points for each of

the components in Figure 3, component #1 has the "steepest" slope and component #6 has the "shallowest" slope. So, if three servicings were selected, they would occur at the minimum cost points for components #1, #2 and #3. Since component #4 has its minimum cost point nearest the servicing time for component #2, it would be replaced with component #2. Similarly, component #5 would be changed with component #3 and component #6 would be changed with component #2. This procedure would then be repeated for the case where four servicings were selected and so on. Although this approach looks promising, it has a logic flaw in that it does not recognise that combining two components with flatter cost curve slopes could result in a subtotal cost curve which was steeper than some of the curves already combined.

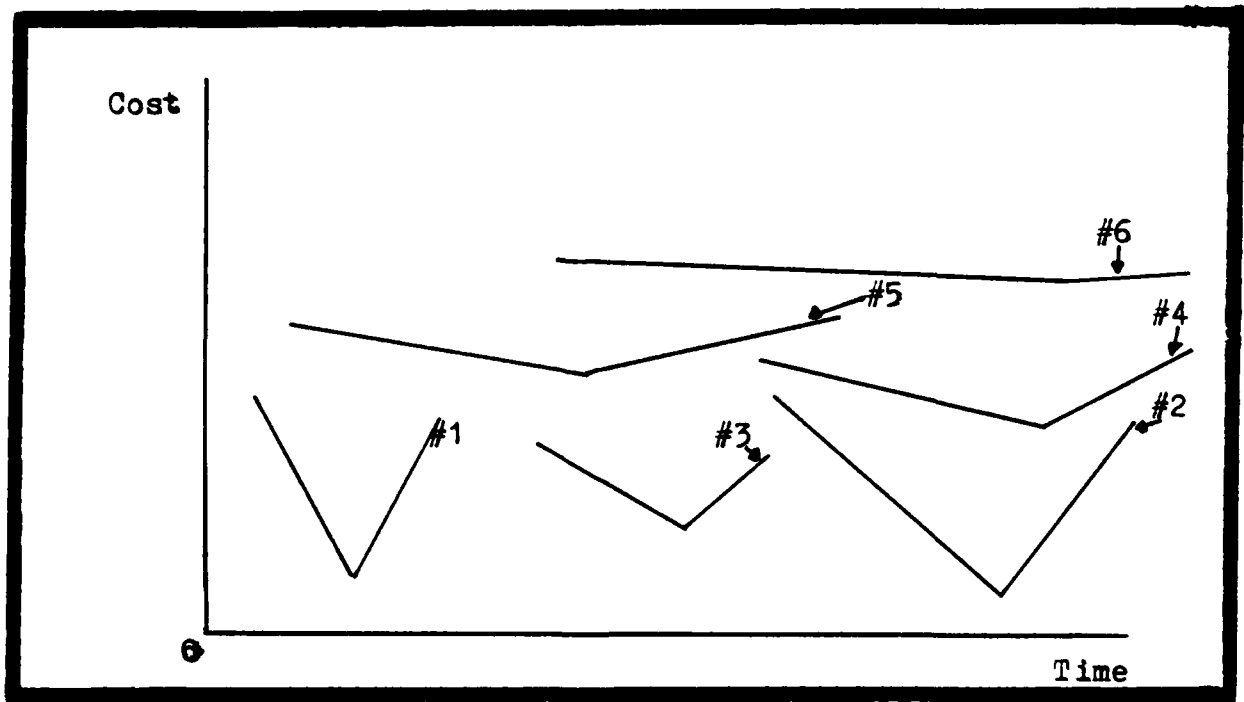


Figure 3. Illustration of First Approach
(Which was Flawed)

Another approach is to move along the "time" axis from the origin adding cost curves as they occur. This aggregation of cost curves is based on the assumption that all of the component cost curves are convex shaped so if the slope to the right of the first minimum cost point is greater than the slope to the left of the component whose minimum cost point is next; then the summation of the two curves will be at a minimum at the first curve's minimum point. The reverse logic applies for when the slope to the right of the first minimum cost point is less than the slope to the left of the second minimum cost point. In this case, the lowest cost sum of these two curves occurs at the second minimum point. This approach is illustrated in Figure 4. As the slope to the right of the minimum cost point for component #1 is greater than the slope to the left of the minimum cost point for component #2, the sum of the two curves is a minimum at the same point as the minimum cost point for component #1. However, this approach is flawed because the minimum point of the sum of two convex curves does not necessarily occur at the minimum point of one of its constituent curves.

The approach finally adopted and found to be workable is based on using a heuristic to divide the components into small groups which all have minimum costs occurring at similar ages. Optimum intervals for these small groups of components are then readily determined by mathematical

iteration because the numbers involved are much smaller.

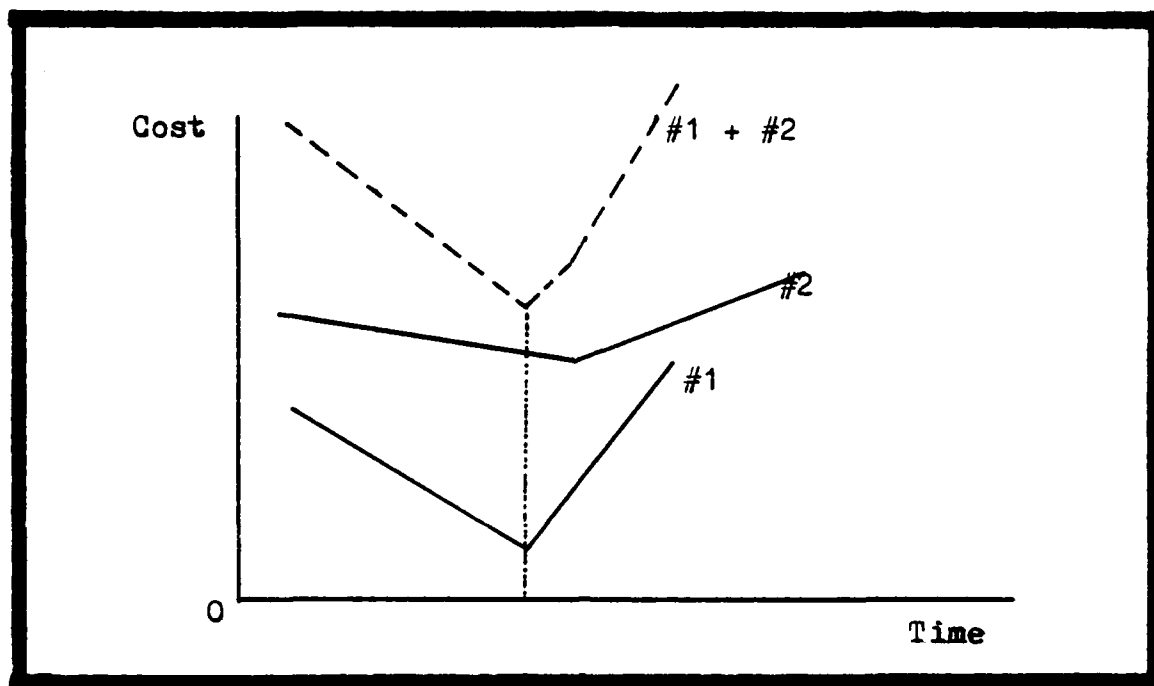


Figure 4. Illustration of Second Approach
(Which was Flawed)

This method is now described as follows:

Step 1: Divide the time axis into a number of cells of equal width. Equal widths are chosen to simplify the computer coding. Note: The number of cells chosen is varied with each iteration of this method to achieve an estimate of the optimal solution.

Step 2: In each cell, determine the lowest cost for each component which is represented in the cell.

Step 3: Starting at the origin (time=0), look at any components which are in both the first and second cells (i.e., cells 1 and 2). For each component which is in both cells, compare its lowest cost point in each cell. If the

cost is lower in cell 2 (compared with cell 1) by an amount greater than the administrative cost, it is clearly more economical to replace the component at some time in cell 2 rather than in cell 1. Thus, it is allocated to cell 2. Conversely, if the lowest cost point in cell 1 plus the administrative cost is less than the lowest point in cell 2, the component is assigned to cell 1. For all of the other components represented in both cell 1 and 2, it is only cost-effective to move them if the following conditions are met:

1. the components all have low points in the same domain (i.e., they do not have mutually exclusive domains);
2. the differences between the low costs in cell 1 and cell 2 all sum to less than the "admin" cost and moving the components will reduce the number of servicings by one. (i.e., the cost of grouping all these components in one cell must be less than the "admin" cost saved by not having a servicing in both cells).

Step 4: Step 3 is repeated for the next pair of cells (i.e., cell 2 and cell 3). Note: This may move a component from cell 2 to cell 3.

Step 5: After using the heuristic described above to

coarsely divide the various components into cell groups, the minimum cost grouping in each cell is determined. This is done by sorting the turning points for all of the components in the cell into ascending time order (i.e., chronologically). Then starting at the cell's left boundary, all components are checked to see if their domain lies in this time. If not, then move to the next turning point time. If all components are represented at that time, the sum of the total costs for each component at that time is found. As this process is repeated for each turning point, the sum of the total costs decreases and then starts to increase. The time at which a lowest value of the sum of total costs occurs is then the replacement age for the components which are grouped in this interval.

Step 6: Step 5 is repeated for each cell and a total cost of the suite of servicings is determined by summing the administrative costs and the minimum "sum of total costs" for each servicing (i.e., group of components).

Step 7: The number of cells is changed and the entire process (Steps 1 through 6) is repeated.

To illustrate the use of this heuristic model, consider the trivial example in Figure 5.

Step 1: The "time" axis is divided into a number of cells of equal width, say 5 cells of width 4 time units.

Step 2: In cell 1, the lowest cost for component #1 is 1 cost unit at 2 time units. The lowest cost for component #2 is 3.5 units at 4 time units. In cell 2, the lowest cost

for component #1 is 1.5, the lowest cost for component #2 is 3 and the lowest cost for component #3 is 2. This determination is repeated for the remainder of the cells.

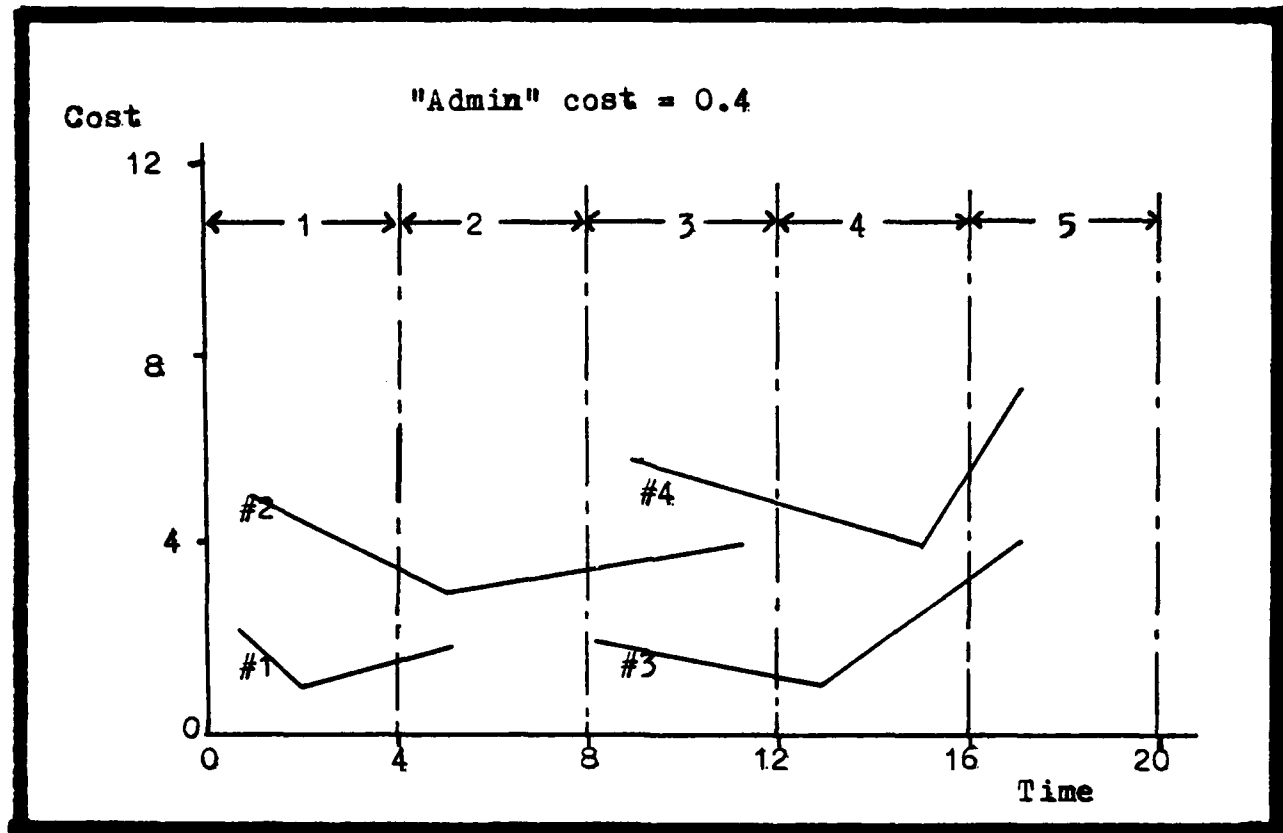


Figure 5. Illustration of Heuristic Method

Step 3: As servicing component #1 in cell 1 instead of cell 2 saves 0.5 cost units and the "admin" cost incurred in this servicing is only 0.4 cost units, component #1 is assigned to cell 1. Similarly, component #2 is assigned to cell 2. Component #3 is not assigned because its domain does not lie in both cells 1 and 2.

Step 4: This repeats step 3 for cells 2 and 3; 3 and 4; 4 and 5.

Step 5: For cell 1, only component #1 is assigned. It has three points of interest which occur at times 1, 2 and 4 and incur costs 2, 1, and 1.5 respectively. Clearly, the lowest cost value is 1 which occurs at time 2. Hence, one servicing should occur at time 2 and it should involve replacing component #1.

Step 6: Repeating the process in step 5 for cell 2, component #2 should be replaced at time 5.

Step 7: After doing the previous six steps for all cells, a new number of cells is selected and the process is repeated.

Applying this model for a number of different cells then results in different total cost values for different number of cells. Intuitively, these total cost values when plotted against the number of cells, should exhibit a minimum point. This is because at one extreme, every component will be replaced at its lowest cost point but an administrative cost will be incurred for each component. At the other extreme, only a few administrative costs will be incurred but most components will not be replaced at their minimum cost points. Somewhere in between these two extremes, there should be a lower cost option where some components are serviced at their minimum cost points while others are not. However, the number of administrative costs should also be kept to the minimum necessary for cost savings.

Validation of the Model

To internally validate the model, test data was fabricated (for 6 hypothetical components) and the model was used to find a near optimal solution. The optimal solution was then determined by mathematical iteration and it was found to agree with the results from the model. The model was also run "backwards" (i.e., from right to left) so Steps 1-6 considered the last cell first, and compared it to the second-last cell, and so on. The model gave the same result in terms of total cost although a different number of cells was required to obtain this result.

The model could not be externally validated. However, to externally validate the model, a suite of servicings computed by the model would have to be implemented. The costs involved in doing maintenance according to this model would then have to be tracked over time to determine if the model provides a close approximation to the actual costs incurred. Due to time constraints, the task of externally validating this type of heuristic model is beyond the capabilities of this research.

Computer Programme Implementation of the Model

A Basic computer programme was written to carry out steps 1-6 of the model. This programme is listed in Appendix E. It was validated by:

1. using dummy data and comparing the results with those calculated by hand; and
2. stepping through each part of the programme with debug statements.

Illustration of the Model

The TTT statistics for the eight components discussed in Chapter IV plus the administrative cost developed in this Chapter were analysed with the computer programme to determine their respective cost functions. Various numbers of cells were considered from 1 cell to 10 cells. The

TABLE IV
Output from the Heuristic Model

No of Intervals	Width (Flying Hrs)	No of Servicings	Total Cost (mhrs/fhrs)
1	Not feasible due to mutual exclusion		
2	Not feasible due to mutual exclusion		
3	2731.5	3	1.15088
4	2048.6	4	1.28403
5	1638.9	4	1.16700
6	1365.7	4	1.16377
7	1170.6	5	1.58562
8	1024.3	5	1.34136
9	910.5	4	1.24453
10	819.5	5	1.52638

resulting costs are listed in Table IV and graphically displayed in Figure 6. The actual results are also contained in Appendix F.

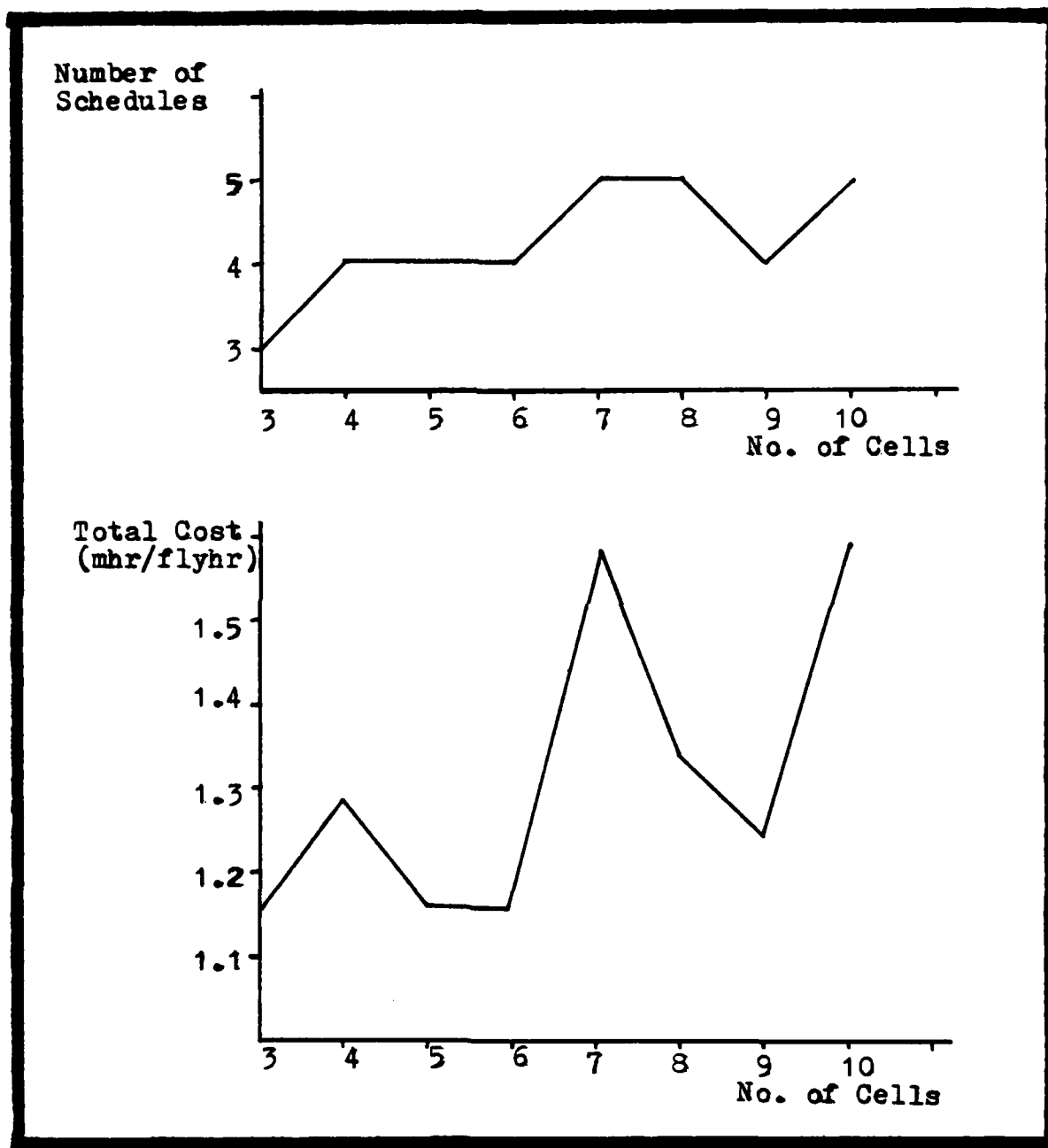


Figure 6. Output From the Heuristic Model

As can be seen from Figure 6, the total cost values as a function of the number of cells did not represent a convex curve shape as was expected. This can be explained by the very few data points that were available for the actual field data. This lack of data meant the model was very sensitive to interval size. Components tended to stay grouped together until the interval width was changed so it excluded another data point and so changed the grouping. If the number of observations of the actual field data was large enough, then there would be a high probability that the estimated optimal suite of servicing schedules would be almost optimal.

However, from Figure 6, it can be seen that the best estimate of the optimum mix of servicing schedules occurred when six intervals were used in the model. This gave a total cost of 1.16377 manhours per flying hour with the eight components being replaced (or overhauled to a good-as-new condition) as follows:

At 1626.4 flying hours, replace: Starter Pnuematic

Control Fuel

Co-ordinator Assembly

Cooler Oil

At 2731.5 flying hours, replace: Valve Temp Datum

At 5463.0 flying hours, replace: Switch Speed Sensing

At 6828.8 flying hours, replace: Generator AC Engine

Act Flap Oil Cooler

Although the actual field data was very limited, it has illustrated the potential usefulness of the model for determining the optimal mix of servicing intervals for a number of components in a complex system.

VI. Conclusion, Implications and Recommendations

In this Chapter, the models developed in both stages of this thesis are placed in perspective.

Meeting the Research Objective

The research objective was to develop a decision logic for determining the optimum maintenance intervals for a complex system. In this research, existing studies and methods for optimizing maintenance intervals for a complex system have been reviewed with the conclusion that a reasonable solution could be obtained by using heuristic methods. Heuristics only provide an estimate of the optimal solution but as the number of observations (i.e., the raw data) increases, the results from the heuristic model more closely approximate the actual solution.

In Chapter V, a heuristic model was developed which met the research objective. This model was then illustrated by using a cost function model based on the TTT statistic (developed in Chapter III) and using actual field data for the RAAF C130H aircraft engine.

Research Questions

The research question, "Can a theoretical computer-based method be developed for optimizing replacement intervals for

a complex system with many components?"; was answered in the affirmative with a heuristic model being developed and computerised.

In answer to the secondary research question of how does total component age affect reliability, the evidence, although limited by a lack of data, indicates that the repair or replacement process does not return components to a "good-as-new" condition.

This research has significant implications for the aircraft maintenance community. At present, aircraft intervals are determined by "expert knowledge" which often results in non-optimal servicing schedules being developed. By using the heuristic model developed in this research and the total cost functions obtained from the TTT statistic, aircraft operators could determine a more optimal suite of servicing schedules and so achieve substantial economies.

The only caveat in the application of this research is the availability of data. Most aircraft operators, including the RAAF and the USAF, aggregate failure data at the aircraft maintenance unit level and then destroy the original failure records for the components. Without component lifetime data the TTT statistic cannot be obtained and component cost functions cannot be derived.

During the course of this research, a number of areas were found which are worthy of further attention.

General

In general, the biggest problem requiring attention is the lack of data. RAAF Maintenance Managers need to change their current policy of aggregating data and then destroying the raw source data. These managers may believe that they are reducing costs by reducing the quantities of stored data but they fail to recognise that a lack of accurate data is preventing optimisation of maintenance intervals for components which exhibit IFR class failure distribution. A shortage of accurate cost data is also a problem that requires management attention.

Recommendations for Future Research

The following areas are recommended for further research:

1. The computer programme for development of the TTT cost function needs to be combined with the computer programme for the heuristic model so that the combination of programmes can be marketed as a user friendly package for those unfamiliar with TTT statistics.
2. The heuristic model developed in Chapter V was based on a constant administrative cost. This

model needs to be modified to consider administrative costs which vary depending upon the components involved.

3. The total cost functions derived from the TTT statistic assumed that components were "good-as-new" after repair. This was proven not to be the case so the cost function model in Chapter III and the heuristic model in Chapter V need to be modified to handle this situation.
4. A sensitivity analysis needs to be done to ascertain how sensitive both models are to variations in failure costs (c_1), replacement costs (c_2) and administrative costs.

APPENDIX A

COMPUTER PROGRAM FOR TTT AGE REPLACEMENT COMPUTATIONS

This computer programme was written in Sanyo Basic version 1.32 to run on a Sanyo MBC-550 personal computer.

```

10 '
20 '
30 '**** PROGRAM FOR TTT PLOTS ****
40 '    (Using truncated and withdrawn data)
50 '
60 '
70 ' --- DEVELOPED BY SQNLDR D.O'HEARN FOR MASTERS THESIS
90 '
100 '
110 '--- LIST OF VARIABLES ---
120 '
130 'A(I)      : Lifetime for i th component
140 'B(K)      : Value for i for the k th failed component
150 'C         :  $C = C2/(C1-C2)$ 
160 'C1        : Cost of failure of component
170 'C2        : Cost of replacement of component
180 'D         : Total number of failed components
190 'F$(I)     : Single letter for TRUNCATED (T),
                FAILED (F) or
200 '          WITHDRAWN (W) component
210 'K         : Counter for failed components
220 'M         : Index of k th failure for truncation
                purposes
230 'MAX       : Temporary variable for sorting in
                Bergman's solution
240 'OPT       : Value of i for the optimum solution
250 'N         : Number of component lives considered
260 'N$        : File name for data files: N$.= input
270 '          N$.DAT=TTT graph
280 '          N$.DBT=line -C
290 'P         : Counter - number of withdrawals in a row
300 'R$        : Single letter for : NEW (N) or EXISTING
                (E) file; or Creating another run
320 'STTT(I)   :  $TTT(I)/TTT(N)$  i.e. scaled value of TTT(I)
330 'STTT1(K)  :  $TTT(K)/TTT(N)$ 
340 'T$        : Temporary variable - sorting F$(I)
350 'TEMP       : Temporary variable - sorting A(I)
360 'TITLE$    : Component name (max 20 characters)

```

(Continued over page)

```

370 'TTT(I)      : Total time on test for i th component
380 'TTT1(K)     : Total time on test for k th FAILED
                  component
390 'Z           : Total number of withdrawals in a row
400 '
410 '
420 '
430 DIM A(80),TTT(80),STTT(80),F$(80),TTT1(40),STTT1(40),
    B(40)
440 '
450 '--- ENTERING DATA ---
460 '
470 INPUT"DO YOU WANT DATA FROM AN EXISTING FILE (E) OR
    DO YOU WANT TO ENTER NEW DATA (N)?" ;R$
480 IF R$="E" THEN GOTO 790
490 '
500 '--- CREATING NEW DATA FILES ---
510 '
520 INPUT"NAME OF FILE FOR NEW DATA";N$
530 OPEN "O",3,N$
540 PRINT"ENTER NAME OF COMPONENT BEING ANALYSED (20
    characters max)"
550 TITLE$=INPUT$(20)
560 PRINT TITLE$
570 I=0
580 PRINT"WHEN OUT OF DATA, TYPE '99999' (i.e. 5 NINES) FOR"
590 PRINT"          THE LIFETIMES VALUE"
600 I=I+1
610 INPUT"ENTER LIFETIME";A(I)
620 IF A(I)=99999! THEN GOTO 670
630 PRINT"DID COMPONENT - FAIL (F)"
640 PRINT"          - HAVE ITS LIFE TRUNCATED (T)"
650 INPUT"          - GET WITHDRAWN (W)";F$(I)
660 IF A(I)<>99999! THEN GOTO 600
670 N=I-1
680 PRINT#3,TITLE$
690 PRINT#3,N
700 FOR I=1 TO N
710 PRINT#3,A(I)
720 PRINT#3,F$(I)
730 NEXT I
740 CLOSE
750 GOTO 910
760 '
770 '--- ACCESSING EXISTING DATA FILES ---
780 '
790 INPUT"NAME OF EXISTING FILE";N$
800 OPEN "I",3,N$
810 INPUT#3,TITLE$
820 INPUT#3,N
830 FOR I=1 TO N
840 INPUT#3,A(I)
850 INPUT#3,F$(I)

```

(Continued over page)

```

860 NEXT I
870 REALN=N
880 '
890 '--- ENTERING COST VALUES ---
900 '
910 INPUT"ENTER C1";C1
920 PRINT C1
930 INPUT"ENTER C2";C2
940 PRINT C2
950 OPEN "O",1,N$+".DAT"
960 OPEN "O",2,N$+".DBT"
970 '
980 '--- SORTING A(I) INTO ORDERED LIFETIMES ---
990 '
1000 LET F=0
1010 FOR I=1 TO N-1
1020 IF A(I)<=A(I+1) THEN GOTO 1100
1030 LET TEMP=A(I)
1040 LET T$=F$(I)
1050 LET A(I)=A(I+1)
1060 LET F$(I)=F$(I+1)
1070 LET A(I+1)=TEMP
1080 LET F$(I+1)=T$
1090 LET F=1
1100 NEXT I
1110 ' IF F=1 THEN ORDER ISN'T PERFECT YET
1120 IF F=1 GOTO 1000
1130 '
1140 '---- TOTAL TIME ON TEST SUBROUTINE ---
1150 '
1160 FOR J=1 TO N
1170 IF J=1 THEN TTT(J)=N*A(J)
1180 IF J=1 GOTO 1200
1190 LET TTT(J)=TTT(J-1)+(N-J+1)*(A(J)-A(J-1))
1200 NEXT J
1210 '
1220 '---- WITHDRAWN DATA ROUTINE ---
1230 '
1240 FOR I= 1 TO N
1250 IF F$(I)<>"W" OR F$(I)<>"w" THEN GOTO 1320
1260 FOR P=1 TO I
1270 IF F$(I-P)="W" OR F$(I-P)="w" THEN GOTO 1300
1280 Z=P
1290 GOTO 1310
1300 NEXT P
1310 TTT(I+1)=TTT(I+1)-TTT(I-Z)
1320 NEXT I
1330 '
1340 '---- TRUNCATION ROUTINE ---
1350 '
1360 FOR I=N TO 1 STEP -1
1370 M=I
1380 IF F$(I)="F" OR F$(I)="f" THEN GOTO 1400
1390 NEXT I

```

(Continued over page)

```

1400 ' M = INDEX OF K TH FAILURE
1410 '
1420 '--- SCALING THE TTT SUBROUTINE ---
1430 '
1440 FOR I=1 TO M
1450 NEXT I
1460 LPRINT,"COMPONENT: ";TITLE$;
1470 LPRINT
1480 LPRINT,"THESE CALCULATIONS ARE BASED ON FILE... ";N$
1490 LPRINT
1500 LPRINT," I "; " T(I) "; "TTT(I) "; " U(I) "; " I/N "; "
TOT COST"
1510 K=0
1520 N=M
1530 FOR I=1 TO N
1540 STTT(I)=TTT(I)/TTT(N)
1550 C=C2/(C1-C2)
1560 IF F$(I)="T" OR F$(I)="W" OR F$(I)="t" OR F$(I)="w"
THEN GOTO 1630
1570 K=K+1
1580 CN=((C+I/N)*(C1-C2))/(STTT(I))
1590 LPRINT,I;A(I);TTT(I);STTT(I);I/N;CN
1600 TTT1(K)=TTT(I) :STTT1(K)=STTT(I) :B(K)=I
1610 IF I=1 THEN PRINT#1,0;0;0
1620 PRINT#1,TTT(I); STTT(I); I/N
1630 NEXT I
1640 D=K
1650 '
1660 '--- BERGMAN'S SOLUTION CALCULATION SUBROUTINE ---
1670 '
1680 LET X=0
1690 LET MAX=0
1700 LPRINT
1710 LPRINT, "X ", " MAX", "OPT I"
1720 FOR I=1 TO D
1730 X=STTT1(I)/((C2/(C1-C2))+B(I)/N)
1740 IF X=MAX THEN PRINT,"PROBLEM WITH TIE"
1750 IF X>MAX THEN LET MAX=X
1760 IF X>MAX THEN LET OPT=B(I)
1770 LPRINT,X,MAX,OPT
1780 NEXT I
1790 LPRINT
1800 LPRINT,"BERGMAN'S OPTIMUM REPLACEMENT AGE= ",A(OPT)
1810 LET A$="BERGMAN'S OPTIMUM REPLACEMENT AGE "
1820 FOR I=1 TO 2
1830 IF I=1 THEN PRINT#2,OPT/N;STTT(OPT)
1840 IF I=2 THEN PRINT#2,-C;0 ELSE GOTO 1850
1850 NEXT I
1860 '
1870 '--- CLOSING AND RESETTNG FILES ---
1880 '
1890 CLOSE: RESET
1900 LPRINT:LPRINT:LPRINT:LPRINT
1910 '

```

(Continued over page)

```
1920 '--- REPEATING THE PROGRAM ---  
1930 '  
1940 INPUT"DO YOU WANT ANOTHER RUN (Y/N) ";R$  
1950 IF R$="Y" OR R$="y" THEN GOTO 470  
1960 END
```

APPENDIX B

JUSTIFICATION FOR DELETION OF TRUNCATED DATA

Let subscript 1 denote truncated life data

Let subscript 2 denote data calculated using the TTT model

The data is provided in the following table:

Component	Mean Trunc. Life	TTT Optimum
Act Flap Oil Cooler	1955.2	1958.1
Generator AC Eng	2305.8	3474.4
Control Fuel	2138.5	1626.4
Valve Temp Datum	2455.7	2172.3
Co-ordinator Assy	3596.1	1385.0
Switch Speed Sens	2767.9	2432.0
Valve Speed Sens	3030.7	913.3
Tank Engine Oil	2273.8	8653.4
Cooler Eng Oil	2569.1	1567.2
Tx Eng Oil Press	1727.7	6569.5
Mean	2288.87	2845.96
Std Deviation	823.14	2522.79

Now test $H_0: u_1 - u_2 = 0$

Vs. $H_1: u_1 - u_2 \neq 0$

where $t_{\text{calc}} = -0.2202$

and $t_{\text{tables}} = 2.086$ for 20 d.f. and 95% confidence interval.

As $-t_{\text{tables}} < t_{\text{calc}} < t_{\text{tables}}$, we cannot reject the null hypothesis that the means are equal.

Now, to test if the sample variances are equal, the F-test is used.

$$\text{Test } H_0 : \sigma_1^2 = \sigma_2^2$$

$$H_1 : \sigma_1^2 \neq \sigma_2^2$$

$$\begin{aligned} \text{where } F_{\text{calc}} &= (2522.79)^2 / (823.14)^2 \\ &= 9.39 \end{aligned}$$

$$\text{and } F_{\text{tables}} = 4.03 \text{ for } \alpha = .025, v_1 = 9, v_2 = 9$$

As $F_{\text{calc}} > F_{\text{tables}}$, the H_0 hypothesis is rejected. Therefore, there is evidence at 95% confidence level to accept the assumption of unequal population variances. This means that if the truncated data is deleted, the data set may not accurately represent the true population. However, as the purpose of the data is to illustrate the heuristic model developed in Chapter V, the truncated data records are deleted to reduce some of the data "noise".

APPENDIX C

COMPARISON OF EFFECTS OF PREVIOUS OVERHAULS ON COMPONENT LIVES

Let subscript 1 be for data for components previously overhauled

Let subscript 2 be for data for new components

From the MAARS 22 reports, the following data was obtained:

$$u_1 = 3430.43$$

$$u_2 = 3970.75$$

$$n_1 = 7$$

$$n_2 = 20$$

$$s_1 = 1688.77$$

$$s_2 = 2117.48$$

Now test $H_0: u_1 - u_2 = 0$

Vs. $H_1: u_1 - u_2 \neq 0$

From calculations, $t_{\text{calc}} = -27.41$

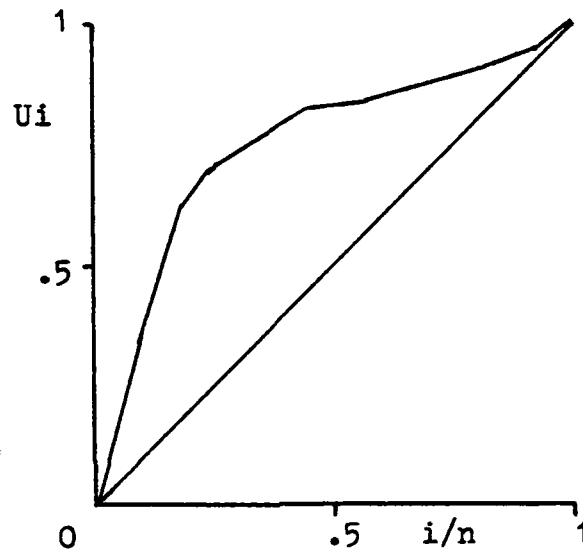
From tables for 95% confidence level and 25 d.f.,
 $t_{\text{tables}} = 1.708$

As $t_{\text{calc}} < -t_{\text{tables}}$, the null hypothesis is rejected. This means the means are not equal so the components life since overhaul is different to its life since new.

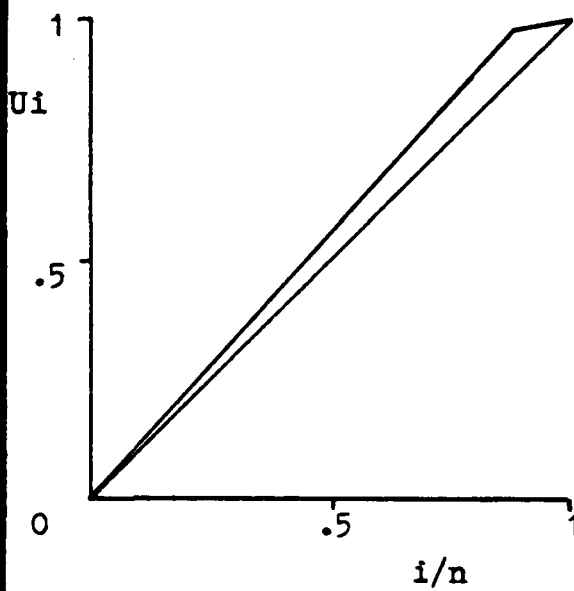
APPENDIX D

TTT CURVES FOR COMPONENTS

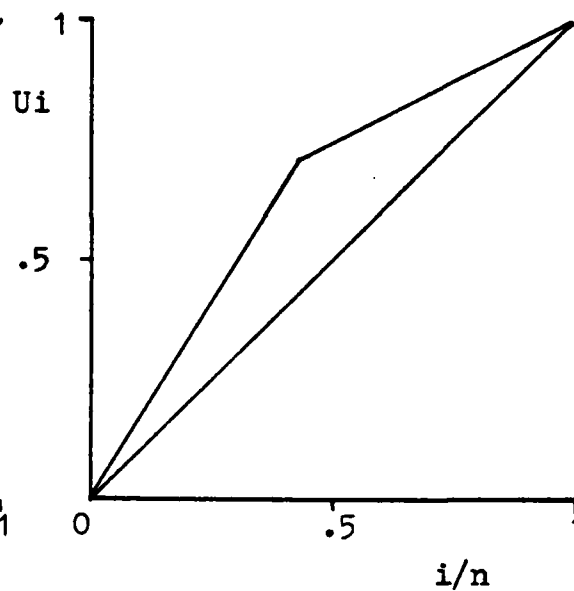
Starter Pneumatic



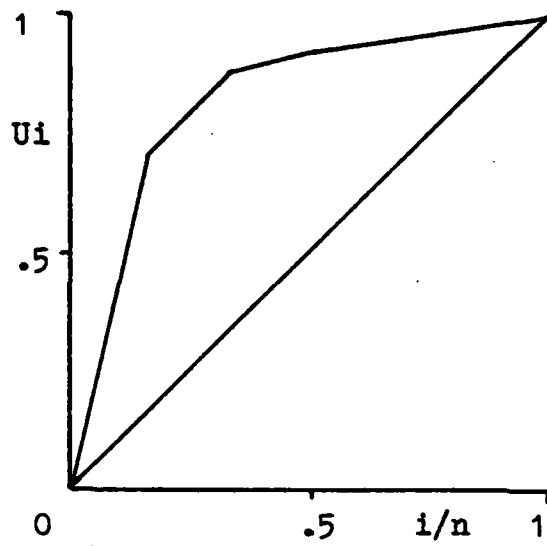
Actuator Flap
Oil Cooler



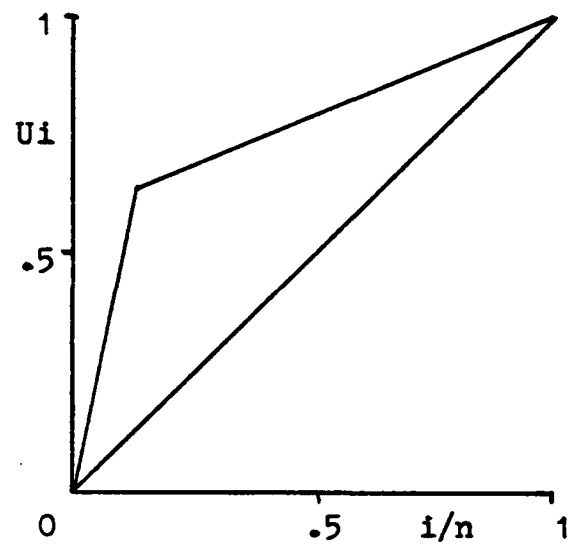
Generator AC
Engine



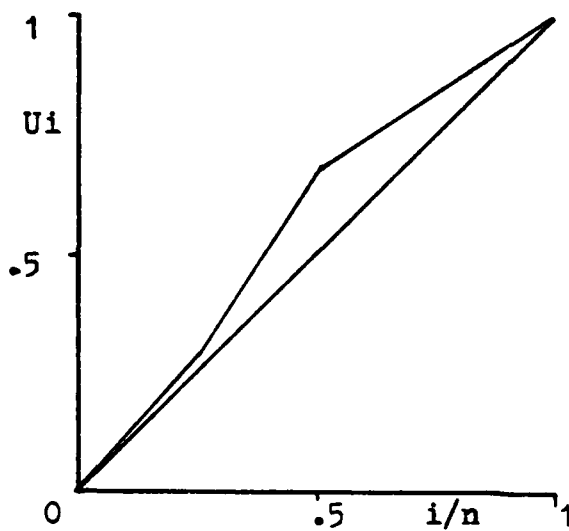
Control Fuel



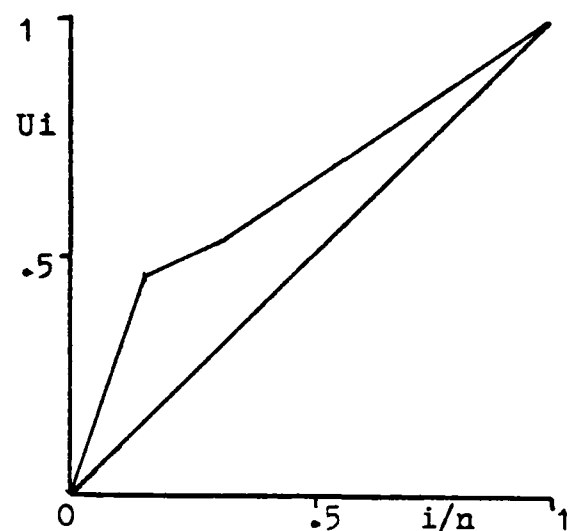
Valve Temp Datum



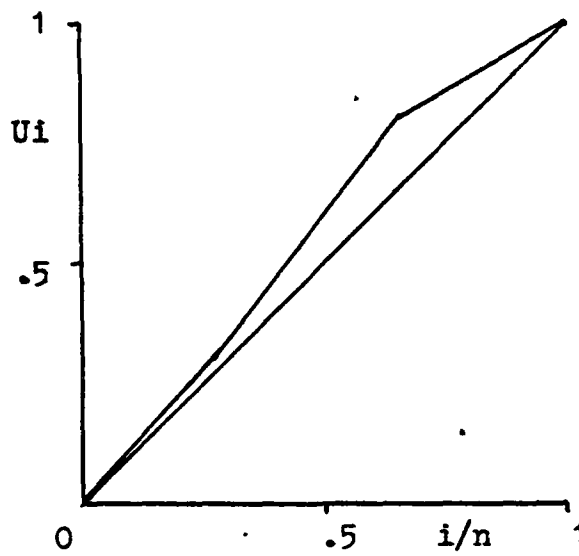
Co-ordinator Assy



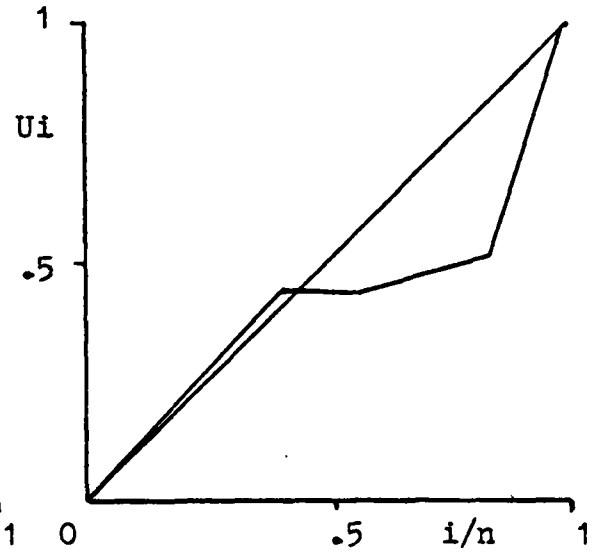
Switch Speed Sensing



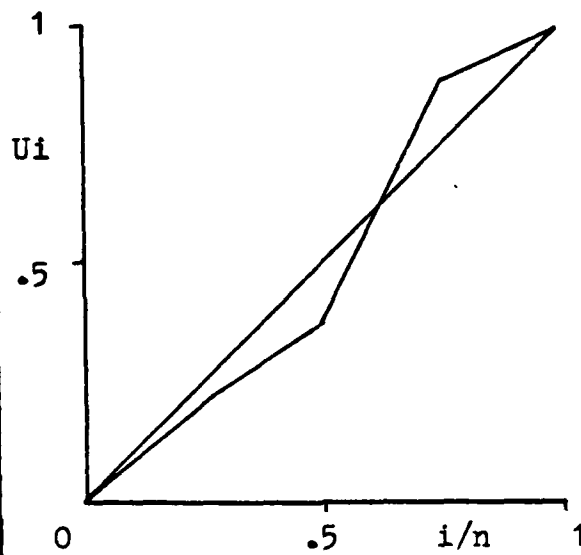
Valve Speed Sensing



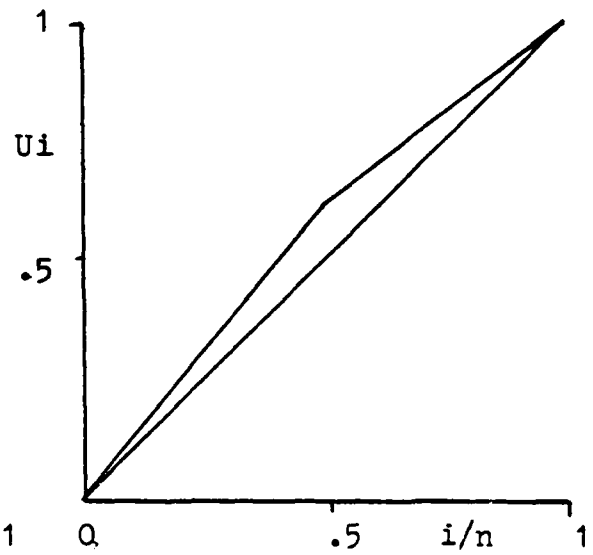
Tank Engine Oil



Tx Engine Oil Press.



Cooler Engine Oil



APPENDIX E

PROGRAMME FOR DETERMINING SERVICING SCHEDULES

This computer programme was written in Sanyo Basic version 1.32 to run on a Sanyo MBC-550 personal computer.

```

10 '
20 '
30 '**** PROGRAM FOR DETERMINING
40 '
50 '**** SERVICING SCHEDULES
60 '
70 '
80 '--- DEVELOPED BY SQLDR D. O'HEARN FOR MASTERS THESIS
90 '
100 '--- LIST OF VARIABLES ---
110 '
120 'ADDCOST      : ADMINSTRATIVE COST - assumed constant
130 'C1(I)       : COST OF FAILURE OF i TH COMPONENT
140 'C2(I)       : COST OF REPLACEMENT OF i TH COMPONENT
150 'COMPNAME$(K) : NAME OF K TH COMPONENT
160 'COMPCOST(K) : COST FUNCTION FOR K TH COMPONENT
170 'TOTCOST(X)  : SUM OF COMPCOSTS
180 'L           : TOTAL # OF COMPONENTS BEING CONSIDERED
                   IN SCHEDULE
190 'NDS(K)      : MAX NUMBER OF DATA SET VALUES FOR K TH
                   COMPONENT
200 'OPT(K)      : OPTIMUM AGE REPLACEMENT FOR K TH ITEM
210 'I(K,J)     : VALUE OF I FOR K TH COMPONENT & J TH
                   DATA VALUE
220 'T(K,J)     : VALUE OF TIME FOR K TH COMPONENT & J TH
                   DATA VALUE
230 'TTT(K,J)   : VALUE OF TTT FOR K TH VALUE & J TH DATA
                   VALUE
240 'CN(K,J)    : COST VALUE FOR TIME FOR K TH COMPONENT &
                   J TH DATA VAL
250 'TIME       : TIME INCREMENT
260 'LGETIM     : LARGEST LIFETIME ON RECORD FOR A
                   COMPONENT
270 'NOINTS     : No OF INTERVALS
280 'TIMINT     : TIME WIDTH OF EACH INTERVAL
290 'INTVL      : INTERVAL NUMBER
300 'AGREG      : SUM OF DIFFERENCES BETWEEN INTERVALS
310 'FLAG       : 0 OR 1 TO INDICATE IF IN 1st
                   INTERVAL OR NOT

```

(Continued over page)

```

320 'LCOST(INTVL,K):COST OF LOWEST VALUE IN 1st INTERVAL
330 'LCOST2(",") : COST OF LOWEST VALUE IN 2nd INTERVAL
340 'TIMVAL      : LOCAL VARIABLE FOR T(K,J)
350 'COSTVAL     : LOCAL VARIABLE FOR CN(K,J)
360 'COMPFLAG    : INDICATES ITEM HAS TO BE AGGREGATED
370 'TURNPT(X)   : TURNPT IN EACH INTERVAL
380 'X           : COUNTER
390 'TPFLAG      : INDICATES IF EACH COST FN PASSES THRU
                  TURNPT
400 'GRANDCT     : SUM OF TOTAL COSTS
410 'TCOST( )    : SUM OF COMPONENT COSTS IN AN INTERVAL
420 'OPTINTVL    : OPTIMUM INTERVAL VALUE
430 'ADMNCOST    : GRANDCT + SUM OF ADMIN COSTS
440 'PFLAG       : INDICATES IF ANY COMPONENTS LIE IN THE
                  INTERVAL
450 '
460 '
470 DIM T(20,20),TTT(20,20),C1(20),C2(20),C(20),I(20,20)
480 DIM TITLES$(20),N(20),CN(20,20)
490 DIM NDS(20),TCOST(200),COMPNAME$(200)
495 DIM TURNPT(2000)
500 '
510 '--- ENTERING DATA ---
520 '
530 INPUT"DO YOU WANT DATA FROM AN EXISTING FILE (E) OR
DO YOU WANT TO ENTER NEW DATA (N) ";R$
540 IF R$="E" OR R$="e" THEN GOTO 900
550 '
560 '--- CREATING NEW DATA FILES ---
570 '
580 INPUT "NAME OF FILE FOR NEW DATA";N$
590 OPEN "O",3,N$+".DAT"
600 INPUT"ENTER NUMBER OF ITEMS TO BE CONSIDERED FOR THE
SCHEDULES";L
610 PRINT#3,L
620 FOR K= 1 TO L
630 PRINT"FOR EACH ITEM, ENTER THE FOLLOWING:";
640 PRINT"NAME OF ITEM (20 characters max.) "
650 TITLES$(K)=INPUT$(20)
660 PRINT#3,TITLES$(K)
670 INPUT"VALUE OF n ";N(K)
680 PRINT#3,N(K)
690 INPUT"VALUE OF FAILURE COST C1 ";C1(K)
700 PRINT#3,C1(K)
710 INPUT"VALUE OF REPLACEMENT COST C2 ";C2(K)
720 PRINT#3,C2(K)
730 C(K)=C2(K)/(C1(K)-C2(K))
740 PRINT#3,C(K)
750 INPUT"NUMBER OF DATA SETS FOR COMPONENT ";NDS(K)
760 PRINT#3,NDS(K)
770 INPUT"OPTIMUM VALUE FOR REPLACEMENT AGE";OPT(K)
780 PRINT#3,OPT(K)
790 FOR J=1 TO NDS(K)
800 INPUT"VALUE OF I ";I(K,J)

```

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```

810 PRINT#3,I(K,J)
820 INPUT"VALUE OF TTT(I) ";TTT(K,J)
830 PRINT#3,TTT(K,J)
840 INPUT"VALUE OF T(I) ";T(K,J)
850 PRINT#3,T(K,J)
860 NEXT J
870 NEXT K
880 GOTO 1120
890 '
900 '--- ACCESSING EXISTING DATA FILES ---
910 '
920 INPUT"NAME OF EXISTING FILE ";N$
930 OPEN "I",3,N$
940 INPUT#3,L
950 FOR K=1 TO L
960 INPUT#3,TITLE$(K)
970 INPUT#3,N(K)
980 INPUT#3,C1(K)
990 INPUT#3,C2(K)
1000 INPUT#3,C(K)
1010 INPUT#3,NDS(K)
1020 INPUT#3,OPT(K)
1030 FOR J=1 TO NDS(K)
1040 INPUT#3,I(K,J)
1050 INPUT#3,TTT(K,J)
1060 INPUT#3,T(K,J)
1070 NEXT J
1080 NEXT K
1090 '
1100 ' --- CALCULATING COST TURNING PTS FOR EACH COMPONENT
1110 '
1120 FOR K=1 TO L
1130 FOR J=1 TO NDS(K)
1140 D=NDS(K)
1150  $CN(K,J) = ((C(K) + I(K,J) / N(K)) / (TTT(K,J) / N(K))) * (C1(K) - C2(K))$ 
1160 NEXT J
1170 NEXT K
1180 '
1190 ' --- PRINTING VALUES FOR EACH COST FUNCTION ---
1200 '
1210 FOR K=1 TO L
1220 PRINT: PRINT TITLE$(K)
1230 PRINT ;"LSN TIME(T) COST VALUE(CN) "
1240 FOR J=1 TO NDS(K)
1250 PRINT;J;T(K,J);CN(K,J)
1260 NEXT J
1270 NEXT K
1280 '
1290 '
1300 '
1310 '--- ENTERING HEADINGS AND ADMIN COSTS ---
1320 '
1330 '

```

(Continued over page)

```

1340 INPUT"ENTER ADMINISTRATIVE COST";ADDCOST
1350 LPRINT:LPRINT
1360 LPRINT"THE ADMIN COST IS CONSTANT AT ";ADDCOST;"
      MANHOURS PER SCHEDULED SERVICING"
1370 LPRINT:LPRINT
1380 '
1390 '
1400 '--- MODULE TO DETERMINE TIME INTERVALS ---
1410 '
1420 LGETIM=0
1430 FOR K=1 TO L
1440 JJ=NDS(K)
1450 IF T(K,JJ) > LGETIM THEN LGETIM=T(K,JJ)
1460 NEXT K
1470 INPUT"ENTER NUMBER OF INTERVALS DESIRED ";NOINTS
1480 TIMINT=LGETIM/NOINTS
1490 LPRINT"FOR ";NOINTS;" INTERVALS, THE ANALYSIS IS AS
      FOLLOWS:" :LPRINT :LPRINT
1500 '
1510 '--- ALLOCATION TO OPTIMUM INTERVALS ---
1520 '
1530 FOR INTVL=1 TO NOINTS
1540 AGREG=0
1550 '
1560 ' DETERMINING IF IN 1ST INTERVAL
1570 FOR K=1 TO L
1580 FLAG(K)=0
1590 LCOST(INTVL,K)=100000!
1600 FOR J=1 TO NDS(K)
1610 TIMVAL=T(K,J)
1620 IF T(K,J)<(INTVL-1)*TIMINT AND T(K,J+1)>INTVL*TIMINT
      THEN TIMVAL=INTVL*TIMINT-.5*TIMINT : COSTVAL=(CN(K,J)+
      CN(K,J+1))/2 : GOTO 1650
1630 IF T(K,J)<(INTVL-1)*TIMINT OR T(K,J)>INTVL*TIMINT THEN
      GOTO 1670
1640 COSTVAL=CN(K,J)
1650 IF COSTVAL<LCOST(INTVL,K) THEN LCOST(INTVL,K)=COSTVAL
1660 FLAG(K)=1
1670 NEXT J
1680 '
1690 ' DETERMINING IF IN BOTH INTERVALS
1700 LCOST2(INTVL,K)=100000!
1710 FOR J=1 TO NDS(K)
1720 TIMVAL=T(K,J)
1730 ' IF COST FN PASSES THRU INTERVAL WITH NO TURNING PTS,
      TAKE AVERAGE VALUE
1740 IF T(K,J)<INTVL*TIMINT AND T(K,J+1)>(INTVL+1)*TIMINT
      THEN TIMVAL=INTVL*TIMINT+.5*TIMINT
      :COSTVAL=(CN(K,J)+CN(K,J+1))/2 :GOTO 1780
1750 'IF COST FN IS NOT IN INTERVAL, GOTO NEXT COMPONENT
1760 IF T(K,J)<INTVL*TIMINT OR T(K,J)>(INTVL+1)*TIMINT THEN
      GOTO 1790
1770 COSTVAL=CN(K,J)
1780 IF COSTVAL<LCOST2(INTVL,K) THEN LCOST2(INTVL,K)=COSTVAL

```

(Continued over page)

```

1790 NEXT J
1800 IF FLAG(K) <> 1 THEN GOTO 1880
1810 AACOST=ADDCOST/((INTVL+.5)*TIMINT)
1820 IF (LCOST(INTVL,K)-LCOST2(INTVL,K))>AACOST THEN
    OPTINTVL(K)=INTVL : GOTO 1880
1830 IF (LCOST2(INTVL,K)-LCOST(INTVL,K))>AACOST THEN
    OPTINTVL(K)=INTVL-1 : GOTO 1880
1840 AGREG=AGREG+(LCOST2(INTVL,K)-LCOST(INTVL,K))
1850 COMPFLAG(K)=1
1860 IF LCOST(INTVL,K)<LCOST2(INTVL,K) THEN
    OPTINTVL(K)=INTVL-1
1870 IF LCOST(INTVL,K)>LCOST2(INTVL,K) THEN
    OPTINTVL(K)=INTVL
1880 NEXT K
1890 '
1900 ' IF NO SAVINGS ACCRUE BY MOVING ALL SCHEDULES, JUMP
1910 IF AGREG<AACOST THEN GOTO 1960
1920 FOR K=1 TO L
1930 IF COMPFLAG(K)=0 THEN GOTO 1960
1940 IF COMPFLAG(K)=1 AND OPTINTVL(K)=(INTVL-1) THEN
    OPTINTVL(K)=INTVL
1950 NEXT K
1960 NEXT INTVL
1970 FOR INTVL=1 TO NOINTS
1980 '
1990 '--- MODULE TO CHECK IF MUTUALLY EXCLUSIVE ---
2000 '
2010 FOR K=1 TO L
2020 STARTVAL=(INTVL-1)*TIMINT : ENDVAL=INTVL*TIMINT
2030 IF OPTINTVL(K)<>INTVL-1 THEN GOTO 2060
2040 IF T(K,1)>(INTVL-1)*TIMINT AND T(K,1)<INTVL*TIMINT AND
    T(K,1)>STARTVAL THEN STARTVAL=T(K,1) : STARTIND=K
2050 IF T(K,NDS(K))>(INTVL-1)*TIMINT AND
    T(K,NDS(K))<INTVL*TIMINT AND T(K,NDS(K))<ENDVAL
    THEN ENDVAL=T(K,NDS(K)) : ENDIND=K
2060 NEXT K
2070 IF STARTVAL>ENDVAL AND STARTVAL>TIMINT*(INTVL-.5) THEN
    Z=STARTIND : OPTINTVL(Z)=INTVL+1 : GOTO 2020
2080 IF STARTVAL>ENDVAL AND ENDVAL<TIMINT*(INTVL-.5) THEN
    Z=ENDIND : OPTINTVL(Z) = INTVL-1 : GOTO 2020
2090 NEXT INTVL
2100 '
2110 '--- MODULE TO DETERMINE OPTIMUM TIME ON EACH INTERVAL
2120 '
2125 XX=0 : X=0
2130 FOR INTVL=1 TO NOINTS
2140 FOR N=1 TO 100 : TCOST(N)=0 : NEXT N
2150 GRANDCT=0
2160 TURNPT(1)=(INTVL-1)*TIMINT
2170 TURNPT(2)=INTVL*TIMINT
2180 X=2
2190 FOR K=1 TO L
2200 IF OPTINTVL(K)<>INTVL-1 THEN GOTO 2270
2210 FOR J=1 TO NDS(K)

```

(Continued over page)

```

2220 IF T(K,J)<(INTVL-1)*TIMINT OR T(K,J)>INTVL*TIMINT THEN
      GOTO 2260
2230 X=X+1
2240 TURNPT(X)=T(K,J)
2260 NEXT J
2270 NEXT K
2280 '
2290 ' SORT VALUES OF TURNPTS IN ASCENDING ORDER
2300 F=0
2310 FOR N=1 TO X-1
2320 IF TURNPT(N)<=TURNPT(N+1) THEN GOTO 2370
2330 TEMP=TURNPT(N)
2340 TURNPT(N)=TURNPT(N+1)
2350 TURNPT(N+1)=TEMP
2360 F=1
2370 NEXT N
2380 'IF ORDER ISNT PERFECT YET
2390 IF F=1 GOTO 2300
2400 '
2410 ' CALCULATE COST AT EACH TURNING PT
2420 FOR N=1 TO X
2430 TCOST(0)=100000!
2440 TPFLAG=0
2450 TIME=TURNPT(N)
2460 FOR K=1 TO L
2470 IF OPTINTVL(K)<>INTVL-1 THEN GOTO 2600
2480 IF TIME<T(K,1) OR TIME>T(K,NDS(K)) THEN
      COMPCOST=100000! :TPFLAG=1 :GOTO 2590
2490 FOR J=1 TO NDS(K)
2500 IF J=NDS(K) THEN COMPCOST=CN(K,J) :GOTO 2590
2510 IF TIME=T(K,J) THEN COMPCOST=CN(K,J) :GOTO 2590
2520 IF TIME>T(K,J) AND TIME<T(K,J+1) THEN GOTO 2550
2530 ' CHECK THAT ALL COMPONENTS ARE AT THAT TURNING PT
2540 NEXT J
2550 '
2560 B=((CN(K,J+1)-CN(K,J))/(T(K,J+1)-T(K,J)))*T(K,J)-
      CN(K,J)
2570 COMPCOST=((CN(K,J+1)-CN(K,J))/(T(K,J+1)-T(K,J)))*TIME-B
2590 TCOST(N)=TCOST(N)+COMPCOST
2600 NEXT K
2610 IF TCOST(N)<TCOST(N-1) AND TCOST(N)>0 THEN
      OPTIND(INTVL)=N
2620 NEXT N
2630 IF TCOST(OPTIND(INTVL))>=100000! AND TPFLAG=1 THEN
      LPRINT"NO FEASIBLE SOLUTION -- MORE INTERVALS ARE
      NEEDED" :GOTO 2920
2640 '
2650 ' PRINT RESULTS
2660 LPRINT"FOR INTERVAL ";INTVL;" FROM ";(INTVL-1)*TIMINT;"
      TO ";INTVL*TIMINT
2670 LPRINT"COMPONENTS ARE: "
2680 PFLAG=0
2690 FOR K=1 TO L
2700 IF OPTINTVL(K)<>INTVL-1 THEN GOTO 2730

```

(Continued over page)

```

2710 PFLAG=1
2720 LPRINT TITLE$(K)
2730 NEXT K
2740 IF PFLAG=0 THEN LPRINT"NIL COMPONENTS IN THIS
      INTERVAL";:LPRINT:LPRINT :GOTO 2810
2750 LPRINT" MIN COST IS ";TCOST(OPTIND(INTVL));" AT TIME
      ";TURNPT(OPTIND(INTVL))
2760 LPRINT
2770 XX=XX+1
2780 LIFE(XX)=TURNPT(OPTIND(INTVL))
2790 TTCOST(XX)=TCOST(OPTIND(INTVL))
2800 GRANDCT=TCOST(OPTIND(INTVL)) + GRANDCT
2810 NEXT INTVL
2820 '
2830 ADMNCOST=0
2840 GRANDCT=0
2850 FOR N=1 TO XX
2860 ADMNCOST=ADMNCOST+ADDCOST/LIFE(N)
2870 GRANDCT=GRANDCT+TTCOST(N)
2880 NEXT N
2890 LPRINT"THE SUM OF THE ADMIN COSTS IS ";ADMNCOST
2900 LPRINT
2910 LPRINT "TOTAL COST OF THIS OPTION IS ";GRANDCT+ADMNCOST
2920 LPRINT:LPRINT:LPRINT
2930 INPUT"DO YOU WANT TO TRY ANOTHER INTERVAL (Y/N)";R$
2940 IF R$="Y" OR R$="y" THEN GOTO 1470
2950 END

```

APPENDIX F

OUTPUT FROM HEURISTIC MODEL

THE ADMIN COST IS CONSTANT AT 11 MANHOURS PER SCHEDULED
SERVICING

FOR 1 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

NO FEASIBLE SOLUTION - - MORE INTERVALS ARE NEEDED

FOR 2 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

NO FEASIBLE SOLUTION - - MORE INTERVALS ARE NEEDED

FOR 3 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 2731.5

COMPONENTS ARE
STARTER PNEUMATIC
CONTROL FUEL
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS 1.05342 AT TIME 1626.4

INTERVAL 2 FROM 2731.5 TO 5463

COMPONENTS ARE
VALVE TEMP DATUM
SWITCH SPEED SENSING

MIN COST IS 3.66413E-02 AT TIME 2731.5

INTERVAL 3 FROM 5463 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 4.80132E-02 AT TIME 5463
SUM OF THE ADMIN COSTS IS .012804
TOTAL COST OF THIS OPTION IS 1.15088

FOR 4 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 2048.63

COMPONENTS ARE
STARTER PNEUMATIC

MIN COST IS .117276 AT TIME 554

INTERVAL 2 FROM 2048.63 TO 4097.25

COMPONENTS ARE
CONTROL FUEL
VALVE TEMP DATUM
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS 1.05994 AT TIME 2172.3

INTERVAL 3 FROM 4097.25 TO 6145.88

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS .027665 AT TIME 4097.25

INTERVAL 4 FROM 6145.88 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 4.97591E-02 AT TIME 6145.88

SUM OF THE ADMIN COSTS IS 2.93939E-02

TOTAL COST OF THIS OPTION IS 1.28403

FOR 5 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 1638.9

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 1638.9 TO 3277.8

COMPONENTS ARE
STARTER PNEUMATIC
CONTROL FUEL
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS 1.05848 AT TIME 1638.9

INTERVAL 3 FROM 3277.8 TO 4916.7

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.42542E-02 AT TIME 3277.8

INTERVAL 4 FROM 4916.7 TO 6555.6

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 2.94696E-02 AT TIME 4916.7

INTERVAL 5 FROM 6555.6 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 5.08067E-02 AT TIME 6555.6

SUM OF THE ADMIN COSTS IS .013983

TOTAL COST OF THIS OPTION IS 1.167

FOR 6 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 1365.75

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 1365.75 TO 2731.5

COMPONENTS ARE
STARTER PNEUMATIC
CONTROL FUEL
CO-ORDINATOR ASSEMBL
COOLER OIL

MIN COST IS 1.05342 AT TIME 1626.4

INTERVAL 3 FROM 2731.5 TO 4097.25

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.37598E-02 AT TIME 2731.5

INTERVAL 4 FROM 4097.25 TO 5463

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 5 FROM 5463 TO 6828.75

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 3.06727E-02 AT TIME 5463

INTERVAL 6 FROM 6828.75 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS .051505 AT TIME 6828.75

SUM OF THE ADMIN COSTS IS 1.44149E-02

TOTAL COST OF THIS OPTION IS 1.16377

FOR 7 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 1170.64

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 1170.64 TO 2341.29

COMPONENTS ARE

STARTER PNEUMATIC

MIN COST IS .282908 AT TIME 1170.64

INTERVAL 3 FROM 2341.29 TO 3511.93

COMPONENTS ARE
CONTROL FUEL
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS 1.18404 AT TIME 2341.29

INTERVAL 4 FROM 3511.93 TO 4682.57

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.44661E-02 AT TIME 3511.93

INTERVAL 5 FROM 4682.57 TO 5853.21

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 6 FROM 5853.21 TO 7023.86

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 3.15321E-02 AT TIME 5853.21

INTERVAL 7 FROM 7023.86 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 5.20039E-02 AT TIME 7023.86

SUM OF THE ADMIN COSTS IS 2.06724E-02

TOTAL COST OF THIS OPTION IS 1.58562

FOR 8 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 1024.31

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 1024.31 TO 2048.63

COMPONENTS ARE
STARTER PNEUMATIC

MIN COST IS .268656 AT TIME 1024.31

INTERVAL 3 FROM 2048.63 TO 3072.94

COMPONENTS ARE
CONTROL FUEL
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS .951072 AT TIME 2048.63

INTERVAL 4 FROM 3072.94 TO 4097.25

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.40638E-02 AT TIME 3072.94

INTERVAL 5 FROM 4097.25 TO 5121.56

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 6 FROM 5121.56 TO 6145.88

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 7 FROM 6145.88 TO 7170.19

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 3.21766E-02 AT TIME 6145.88

INTERVAL 8 FROM 7170.19 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS .052378 AT TIME 7170.19

SUM OF THE ADMIN COSTS IS .023012

TOTAL COST OF THIS OPTION IS 1.34136

FOR 9 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 910.5

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 910.5 TO 1821

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 3 FROM 1821 TO 2731.5

COMPONENTS ARE
STARTER PNEUMATIC
CONTROL FUEL
CO-ORDINATOR ASSEMBLY
COOLER OIL

MIN COST IS 1.13227 AT TIME 1821

INTERVAL 4 FROM 2731.5 TO 3642

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 5 FROM 3642 TO 4552.5

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.45838E-02 AT TIME 3642

INTERVAL 6 FROM 4552.5 TO 5463

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 7 FROM 5463 TO 6373.5

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 8 FROM 6373.5 TO 7284

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 3.26779E-02 AT TIME 6373.5

INTERVAL 9 FROM 7284 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 5.26997E-02 AT TIME 7284

SUM OF THE ADMIN COSTS IS .012297

TOTAL COST OF THIS OPTION IS 1.24453

FOR 10 INTERVALS, THE ANALYSIS IS AS FOLLOWS:

INTERVAL 1 FROM 0 TO 819.45

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 2 FROM 819.45 TO 1638.9

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 3 FROM 1638.9 TO 2458.35

COMPONENTS ARE
STARTER PNEUMATIC
CO-ORDINATOR ASSEMBLY

MIN COST IS .895704 AT TIME 1638.9

INTERVAL 4 FROM 2458.35 TO 3277.8

COMPONENTS ARE
CONTROL FUEL
COOLER OIL

MIN COST IS .51259 AT TIME 2458.35

INTERVAL 5 FROM 3277.8 TO 4097.25

COMPONENTS ARE
VALVE TEMP DATUM

MIN COST IS 1.42542E-02 AT TIME 3277.8

INTERVAL 6 FROM 4097.25 TO 4916.7

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 7 FROM 4916.7 TO 5736.15

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 8 FROM 5736.15 TO 6555.6

COMPONENTS ARE
NIL COMPONENTS IN THIS INTERVAL

INTERVAL 9 FROM 6555.6 TO 7375.05

COMPONENTS ARE
SWITCH SPEED SENSING

MIN COST IS 3.30789E-02 AT TIME 6555.6

INTERVAL 10 FROM 7375.05 TO 8194.5

COMPONENTS ARE
GENERATOR AC ENGINE
ACT FLAP OIL COOLER

MIN COST IS 5.30372E-02 AT TIME 7375.05

SUM OF THE ADMIN COSTS IS 1.77117E-02

TOTAL COST OF THIS OPTION IS 1.52638

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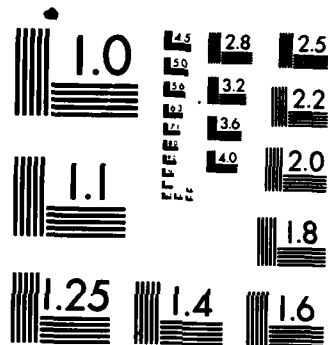
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Scheduled maintenance is considered one of the largest costs of aircraft ownership. For some components that exhibit an increasing failure rate, this cost can be minimized by changing the components at their optimal age replacement intervals which can be determined using the Total-Time-on-Test statistic. However, the age replacement model treats all components as separate entities and does not recognise economies that can be achieved by changing groups of components at the same time. This study develops a heuristic model for determination of near optimal groupings of components and the replacement intervals for these components. This heuristic model is illustrated using actual field data for a number of components fitted to the C130H aircraft engines operated by the Royal Australian Air Force. (THESIS).

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